ESTCP
Cost and Performance Report

(EW-201242)

Zinc Bromide Flow Battery Installation for Islanding and Backup Power

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ESTCP

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This project demonstrated that microgrids with low-cost, large-scale Energy Storage Systems (ESS) have the potential to enhance energy security on military installations by facilitating integration of more renewable energy (RE) and reducing single-point-of-failure vulnerabilities associated with traditional electric service and back-up generators. The first objective was to demonstrate that an ESS enables the use of existing RE systems that normally are unavailable during a grid outage to "island" a building circuit without a diesel generator. The second objective was to demonstrate that an ESS can peak shave for demand charge avoidance.

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Zinc Bromide, Flow Battery Installation, Islanding, Backup Power, Advanced Energy, Advanced Metering Infrastructure, Current Transducer, Energy Storage System, Energy System Integration Facility, Human-Machine Interface, Microgrid Control System, Photovoltaic, Renewable Energy, Total Lifecycle Cost

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ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
AE	Advanced Energy
AMI	Advanced Metering Infrastructure
ANSI/NEMA	American National Standards Institute, Inc./National Electrical Manufacturers Association
BMS	Battery Management System
BMS	Battery Management System
C^2	Command and Control
CDF	Customer Damage Function
CF	Crest Factor
CT	Current Transducer
DC	Direct Current
DDC	Direct Digital Controller
DIACAP	Department of Defense Information Assurance Certification and Accreditation Process
DoD	Department of Defense
ESS	Energy Storage System
ESIF	Energy System Integration Facility
ESTCP	Environmental Technology Certification Program
FAT	Factory Acceptance Testing
HMI	Human-Machine Interface
HVAC	Heating, Ventilation, and Air Conditioning
IA	Interconnect Agreement
IEEE	Institute of Electrical and Electronics Engineers
IPEM	Intelligent Power and Energy Management
IPEM-C^2	Intelligent Power and Energy Management Command and Control
IT	Information Technology
MCAS	Marine Corps Air Station
MCS	Microgrid Control System
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PCC	Point of Common Coupling
PF	Power Factor
PV	Photovoltaic

RE	Renewable Energy
RMF	Risk Management Framework
ROICC	Resident Officer in Charge of Construction
SDG&E	San Diego Gas & Electric
TLC	Total Lifecycle Cost
TOU	Time of Use
TRL	Technology Readiness Level
UCS	Universal Connectivity Server
UL1741	Underwriters Laboratory Inc.'s Standard for Safety for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
UPV	Uniform Present Value
Zn/Br	Zinc Bromide

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EXECUTIVE SUMMARY

This project demonstrated that microgrids with low-cost, large-scale Energy Storage Systems (ESS) have the potential to enhance energy security on military installations by facilitating integration of more renewable energy (RE) and reducing single-point-of-failure vulnerabilities associated with traditional electric service and back-up generators.

OBJECTIVES OF THE DEMONSTRATION

There were two main objectives of this project. The first objective was to demonstrate that an ESS enables the use of existing RE systems that normally are unavailable during a grid outage to "island" a building circuit without a diesel generator. The current large deployments of renewable photovoltaic (PV) systems that have been installed by the Department of Defense (DoD) give incentive to this objective. These systems have built-in safety features such as Underwriters Laboratory Inc.'s Standard for Safety for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources (UL1741) that disable the systems in the event of a grid outage. This project intended to demonstrate that an ESS can provide voltage control capability in islanding operations that allows the functionality of existing PV systems in microgrid mode at high penetration levels.

The second objective was to demonstrate that an ESS can peak shave for demand charge avoidance. Many DoD facilities have been attempting to reduce their operational energy costs by implementing a variety of energy efficiency and RE programs. One of the biggest costs to many facilities is not the cost of energy purchases but the demand charge issued to the facility based on its load profile. This project was designed to allow the ESS to be programmed to charge/discharge according to a defined peak shaving schedule and assess how this changes the load profile seen at the meter of the circuit.

TECHNOLOGY DESCRIPTION

There were two types of technologies demonstrated in this project. The first was a novel design of a Zinc Bromide (Zn/Br) flow battery manufactured by Primus Power (Figure 1). The second was the Intelligent Power and Energy Management (IPEM) Microgrid Control System (MCS) developed by Raytheon.

Figure 1. Image of Installed ESS at MCAS Miramar Outside of Building 6311.

The traditional Zn/Br cell design uses carbon-coated felt paper as the electrode surface. The cells also have two separate electrolyte tanks for capturing the anolyte and catholyte separately during charge and discharge. Traditional Zn/Br cells need to be replaced after 1,500 cycles, which would constitute replacement every 4.1 years if cycled daily. Primus Power takes a different approach to their Zn/Br cells. Instead of using carbon-coated felt paper for their electrodes, Primus utilizes an activated solid titanium electrode for its Zn plating surfaces. Using a titanium electrode allows Primus to use a single flow loop of electrolyte as opposed to dual flow loops and to eliminate the need for an ion exchange membrane, an early failure mechanism in traditional Zn/Br cells. This reduces the number of tanks and pumps required for managing the electrolyte. The titanium electrodes also provide better energy density when compared to traditional Zn/Br: 3.1 kWh/ft^2 compared to 1.7 kWh/ft^2.

This project also demonstrated the use of Raytheon's IPEM MCS, a model-based energy system planning and Command and Control (C^2) technology, as a means to improve energy security and efficiency while reducing operational energy costs at Navy facilities. The IPEM MCS enables microgrid systems modelling in a Matlab Simulink environment during the design process, simulating normal operation as well as off-nominal conditions. Simulink auto-code generation is then used to generate target executables and link with external libraries. This allowed the control algorithms to be designed against component models and reduced system integration risk by making apparent the behavior of the system as its design matured over time.

DEMONSTRATION RESULTS

This project conducted both grid-tied and islanding mode demonstrations to determine the capabilities of the microgrid against the performance objectives. A summary of the demonstration results is shown in Table 1 below.

Table 1. Summary of Demonstration Results

Perf. Objective	Results
Islanding Duration (hrs)	Building loads were met by ESS and PV for 5 hours 10 minutes meeting power quality standards of IEEE1547.4. ESS is capable of 7 hours 10 minutes
Building Load Reductions (%)	Building loads were able to be manually increased and decreased; increased by 68% when compared to baseload during islanding test
Switchover Time (minutes)	Switchover from grid-tied to islanding mode was 4 minutes
ESS Energy Storage Capacity (kWh)	ESS was able to discharge 390 kWh in the lab and 290 kWh in the field
Peak Demand Reduction (kW)	ESS was able to store energy during off peak time and discharge 100 kW during peak time for 2 hours and 45 minutes

IMPLEMENTATION ISSUES

One of the key challenges of this demonstration was working with a technology that was still in its final development phases. Fielding technologies that have been breadboard validated in lab environments is always a challenge and requires iterations and lessons learned to optimize designs. When Primus was selected as the ESS supplier, the team had to manage a company that had promising technology despite their system being lower on the Technology Readiness Level (TRL) scale than the original proposed supplier (Primus was at TRL4). This required the team to simultaneously manage and scale up a promising technology that was in final development. The team was challenged with making hard decisions to continuously balance project performance, risk, and cost to meet the intent of the demonstration objectives within budget.

As this program spanned multiple years, the process of obtaining the Interconnect Agreement (IA) from San Diego Gas & Electric (SDG&E) took some patience and effort. The use of large-scale energy storage in microgrid capacities is new to the utility industry for behind-the-meter applications. Thus the IA process is changing in real time for utilities to adapt to how these systems will be deployed. This project was subject to some of the real-time changes as a few iterations of the application were required due to changing application requirements. Ultimately the IA and permit to operate were granted due to the hard work of multiple parties; however, it is still unclear if there is a well-defined process for getting IAs in place for microgrids.

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1.0 INTRODUCTION

This Environmental Security Technology Certification Program (ESTCP) effort demonstrates the energy security and cost benefits of implementing a Zn/Br Flow Battery-based ESS at the Marine Corps Air Station (MCAS) located at Miramar, California. The effort integrates an innovative Zn/Br Flow Battery and IPEM technologies with the existing MCAS infrastructure, providing energy security and islanding capability.

Improving energy security and reducing consumption are key strategic objectives of the DoD. Achievement of these objectives is limited by commercial power grid vulnerabilities and intermittencies of available renewable resources. Low-cost, large-scale ESSs are needed to address these limitations. Energy storage is a preferred approach to enable off-grid “islanding,” improving energy security through grid-independent operation. The ESS provides a reliable source of energy in the event of a cyber or physical attack, natural disaster, or technical malfunction.

This project started in the middle of 2012 and concluded demonstrations at the end of 2015. Modifications to existing MCAS Miramar infrastructure were required to accommodate the ESS and allow for islanding operations. The system design phase occurred from 2012 to 2014 and went through changes in the supplier of the Zn/Br Flow Battery at the beginning of the program. The pre-construction phase for the program started in the fall of 2014 and the construction started in the spring of 2015. The new utility switchgear and ESS were installed and commissioned at the end summer of 2015. The demonstration phase of the project started in the fall of 2015 and concluded at the end of 2015.

This project was intended to demonstrate that an ESS can be used as a replacement for conventional diesel generators for emergency back-up power and that an ESS can function with renewable energy systems within a microgrid islanding operation to enhance energy security. This project also intended to show that an ESS can be used for economic benefits by changing the load profile of a building by charging and discharging the battery according to a controlled schedule.

1.1 BACKGROUND

The MCAS Miramar has completed a significant study for locating and sizing RE generation in order to demonstrate progress towards reaching net-zero operation (i.e., a military installation that produces as much energy on or near the installation as it consumes in its buildings and facilities). During the initial study, ESSs were briefly discussed but not actively pursued due to constraints of previous programs. MCAS Miramar identified a need to manage the variable power generation of the installed RE systems without adding additional diesel-generating sources. To improve a base’s overall energy security, an ESS was intended to allow islanding of a building circuit utilizing the existing RE without the need of a diesel generator.

1.2 OBJECTIVES OF THE DEMONSTRATION

There were two main objectives of this project. The first objective was to demonstrate that an ESS enables the use of existing RE systems that normally are unavailable during a grid outage to island a building circuit for 72 hours without a diesel generator. The current large deployments of renewable PV systems that have been installed by the DoD give incentive to this objective.

The majority of these PV systems were installed to meet RE goals without considering their interaction with microgrid and islanding energy security scenarios. This resulted in systems with built-in safety features such as UL1741 that disable the RE systems in the event of a grid outage, rendering them unusable. This project intended to demonstrate that an ESS could provide voltage control capability in islanding operations that allow the functionality of existing PV systems in microgrid mode at high penetration levels. This will enhance the energy security of the base in the case of an extreme event (e.g., cyber attack, utility maintenance, or natural disaster), demonstrating that energy storage enabled microgrids provide increased capability over existing PV installations.

The second objective was to demonstrate that an ESS can peak shave for demand charge avoidance. Many DoD facilities have been attempting to reduce their operational energy costs by implementing a variety of energy efficiency and RE programs. One of the biggest costs to many facilities is not in the cost of energy purchases but in the demand charge issued to the facility based on its load profile. This project was designed to allow the ESS to be programmed to charge/discharge according a defined peak shaving schedule, showing that a Zn/Br system can charge during off-peak hours and discharge during peak hours thereby reducing peak load by the power output of the battery. The intent of this objective was to show that energy storage can provide economic benefit in addition to improved energy security.

The field demonstration for this project created operational scenarios for which the two main objectives could be tested. To demonstrate the energy security improvement, the project set up a scenario where power to the microgrid circuit was interrupted and the system would need to provide back-up power for the outage to meet the load requirements of the microgrid. To demonstrate the peak shaving capabilities, the project set the microgrid system so that the ESS could charge and discharge on a user-created schedule and data could be collected on the system's capability to peak shave during defined hours.

1.3 REGULATORY DRIVERS

The National Defense Authorization Acts 2010–2012 and Energy Independence and Security Act of 2007 have shaped the Navy's microgrid strategy, creating five major energy goals (Figure 2) issued by the Secretary of the Navy and shared with the other branches of the military.

Reduce Energy Consumption and Intensity	• By 2020, the Navy will reduce energy consumption and intensity by 50% from a 2003 baseline.
Power from Renewable Sources	• By 2020, 50% of total ashore energy will come from renewable sources.
Net-zero Installations	• By 2020, 50% of installations will be net-zero consumers.
Reduce Non-tactical Petroleum Use	• By 2015, reduce petroleum used in commercial vehicle fleet by 50% from a 2009 baseline.
Increase Energy Security	• Provide reliable, resilient, and redundant power to increase the energy security of mission-critical assets.

Figure 2. Energy Goals from the Secretary of the Navy (Cullom, 2010).

The goal of increased energy security drives this project. It is common for military bases to get their power from local utility companies, whose power distribution networks can be vulnerable to events such as extreme weather or even cyber-attacks. The San Diego area was subject to an 11-hour blackout in 2011 due to an error during routine maintenance of the distribution system (Figure 3). Currently, the necessary back-up generation systems rely on diesel generators. To meet energy goals, the Navy is exploring ways to leverage their RE investments to replace diesel-burning systems. The Navy is also looking for creative ways that it can use microgrids and energy storage to improve its load profile to avoid high peak charges and participate in economic incentive programs such as demand response.

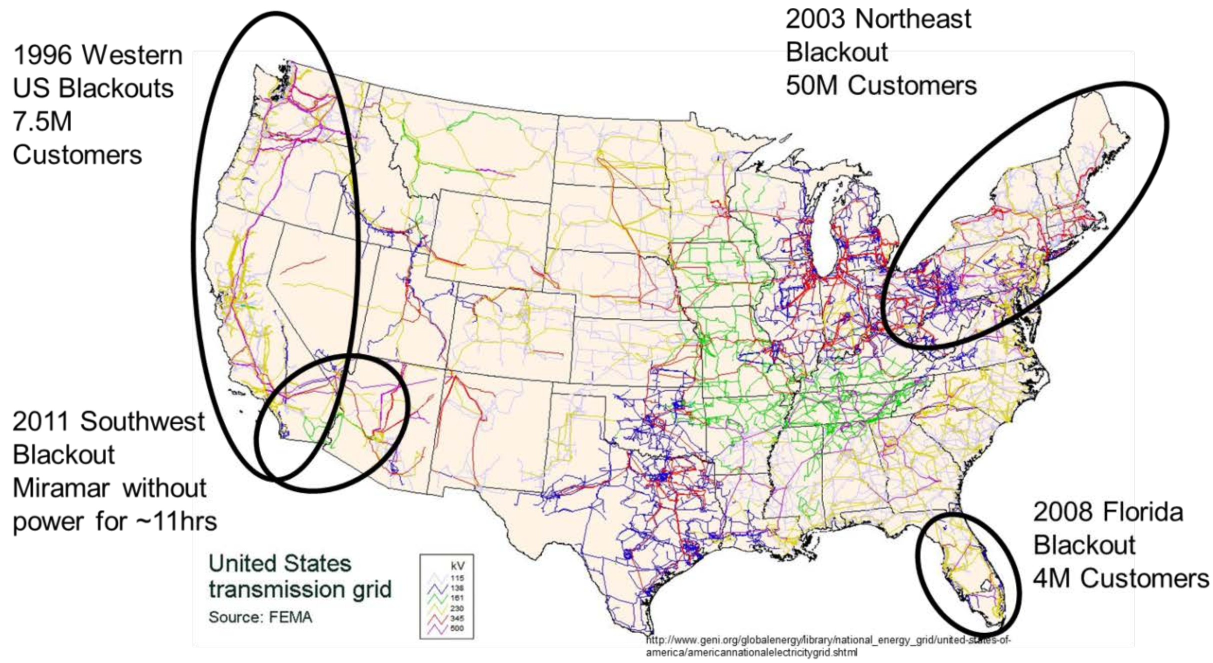

Figure 3. Image of the U.S. Electrical Distribution System Taken from the FEMA Website.

Energy storage and advanced controls can play a key role in meeting the energy goals and mission needs of our military installations. The existing electrical distribution system was built around the production/use principle that electricity must be produced when it is needed and consumed once it is produced. This principle works when a generation network that is monitored and controlled predictably is in place. The ability to control generation has become more difficult with the increase of RE systems such as solar PV and wind turbines. Both PV and wind systems generate power based on unpredictable cycles of nature. At very low levels of RE penetration the grid can be balanced by the existing generator network. At higher levels of RE penetration, however, stability issues arise, and the distribution system needs advanced controls to keep the network balanced by curtailing RE generation to acceptable levels. The ability to store excess energy critically enables increased levels of RE penetration.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

Technology Description

The Zn/Br flow battery technology manufactured by Primus Power was chosen as the storage provider over other storage technologies for several reasons. The key determining factors for islanding and renewables integration applications for Miramar were: low cost, energy storage capacity, intelligent system control, transportability, cycle life, system lifetime, and safety.

Traditional Zn/Br batteries contain a solution of zinc bromide in two tanks. During battery charging, zinc is electroplated on the anode and bromine is sequestered in a polybromide complex that is stored in the electrolyte storage tank. On discharge, the polybromide complex is returned to the battery stacks, and zinc is oxidized back into the electrolyte solution, forming the identical Zn/Br solution the unit started with (Figure 4). This type of battery is the product of many years spent developing proper plating systems in a novel storage approach.

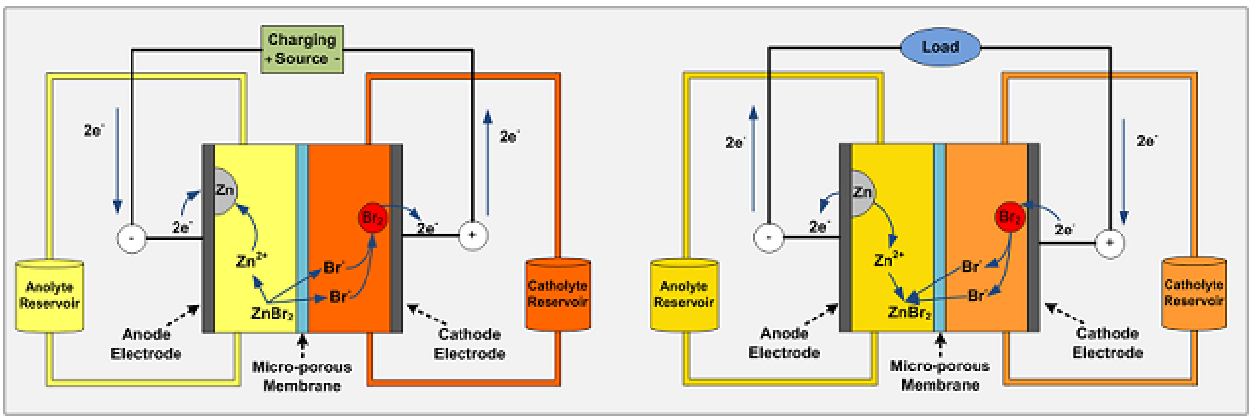

Figure 4. Schematic of a Traditional Zn/Br Cell with Two Electrolyte Flow Loops.

The traditional Zn/Br cell design uses carbon-coated felt paper as the electrode surface. The cells also have two separate electrolyte tanks for capturing the anolyte and catholyte separately during charge and discharge. The separator membranes and carbon paper often are subject to degradation and contamination, making them a common failure mechanism amongst Zn/Br batteries that require recurring replacement. Traditional Zn/Br needs to be replaced after 1,500 cycles, which would constitute replacement every 4.1 years if cycled daily.

Primus Power took a different approach to their Zn/Br cells. Instead of using carbon-coated felt paper for their electrodes, Primus uses an activated solid titanium electrode for its Zn plating surfaces. Using a titanium electrode allows Primus to use a single flow loop of electrolyte as opposed to dual flow loops and eliminates the need for an ion exchange membrane, an early failure mechanism in tradition Zn/Br cells. This reduces the number of tanks required and pumps for managing the electrolyte (Figure 5). The titanium electrodes also provide better energy density when compared to traditional Zn/Br: 3.1 kWh/ft^2 compared to 1.7 kWh/ft^2.

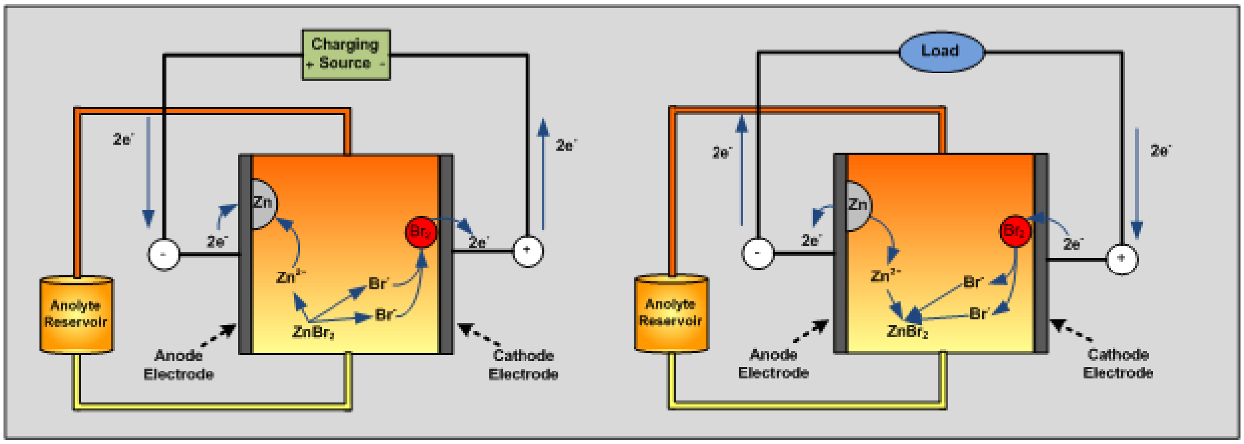

Figure 5. Schematic of Primus' Approach to a Zn/Br Cell Using a Solid Titanium Electrode and a Single Flow Loop of Electrolyte.

Primus' ESS has three integrated main subsystems. Primus uses a 30 kW building block called an EnergyCell to build their EnergyPod system. The EnergyPod, containing the Zn/Br EnergyCells, is connected to a PowerBox that contains the power electronics of the ESS as well as the battery management system (BMS). The ESS also has a chiller to provide cooling. The ESS was specified at the onset of this program to be 250 kW nominal power and 1 MWh of energy capacity at a C/4 discharge rate. During initial tests of the EnergyCells, Primus determined that 14 EnergyCells would be required to achieve the project goals for islanding and peak shaving. The EnergyPod system was ultimately designed to be packaged in a 40 ft container coupled with the PowerBox that was housed in a 20 ft container. A rendering of the Primus ESS is shown in Figure 6.

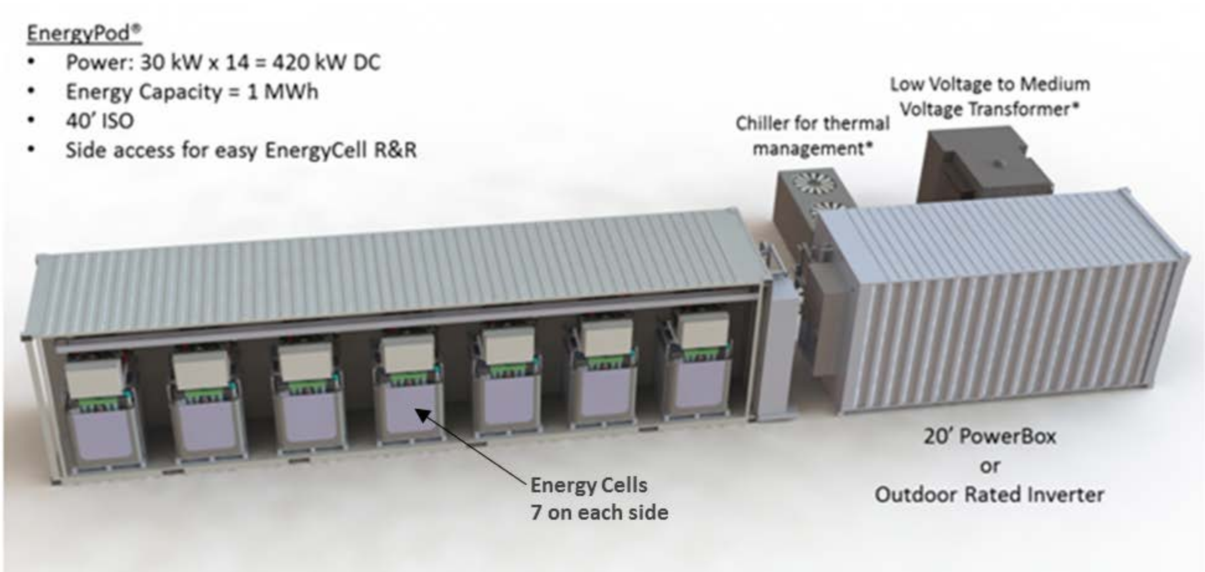

Figure 6. Illustration of Primus' ESS, Complete with EnergyPod (Zn/Br EnergyCells), PowerBox (power electronics), and Thermal Management.

Raytheon's IPEM MCS is a model-based energy system planning and command and control technology. The MCS was the brain of this demonstration microgrid and was comprised of a cyber-hardened IPEM Microgrid Controller (Figure 7, left), IPEM Human-Machine Interface (HMI) (Figure 7, right) and a variety of networking equipment and sensors. The IPEM Controller ran the IPEM Command and Control (IPEM-C^2) software, which provided supervisory control for the microgrid and executed energy management algorithms to operate the microgrid. The energy management algorithms for this demonstration were developed using model-driven software design techniques employing a high-fidelity energy flow model of the system. Measured generation and load data was used to evaluate algorithm efficacy prior to generation of executable code for implementation on the IPEM Controller. This simulated normal operation as well as off-nominal conditions. Auto-code generation was then used to generate the target executable loaded onto the IPEM Controller and linked with external libraries.

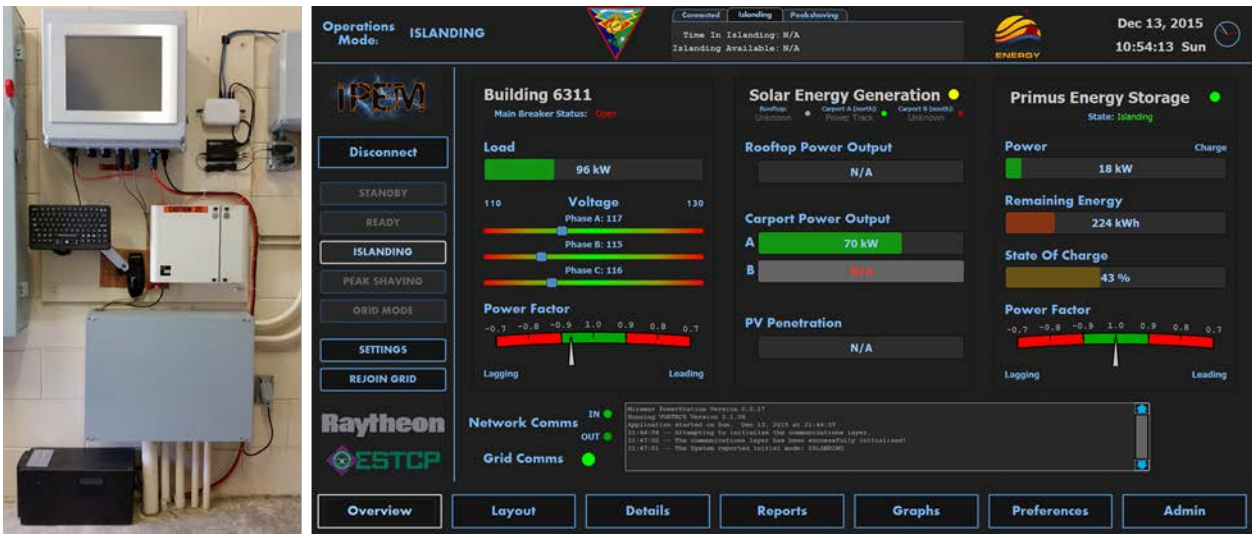

Figure 7. Raytheon's IPEM MCS Installed at MCAS Miramar (left), and HMI Screenshot of the System Operating While Islanding (right).

TECHNOLOGY DEVELOPMENT

The developmental timeline for Primus' Zn/Br technology is summarized in Figure 8 below. Primus' early development started in 2009. When Primus was put under contract for this project in late 2012, they were operating at TRL4. They progressively matured their technology to TRL5 after third-party testing of their 30 kW EnergyCell unit was completed by Sandia National Laboratory (SNL) in the fall of 2013. Primus' technology was then promoted to TRL6 at the conclusion of the MCAS Miramar demonstration, which transferred proof of concept to field production use. The following section will describe the TRL advancement of Primus' technology leading up to the demonstration.

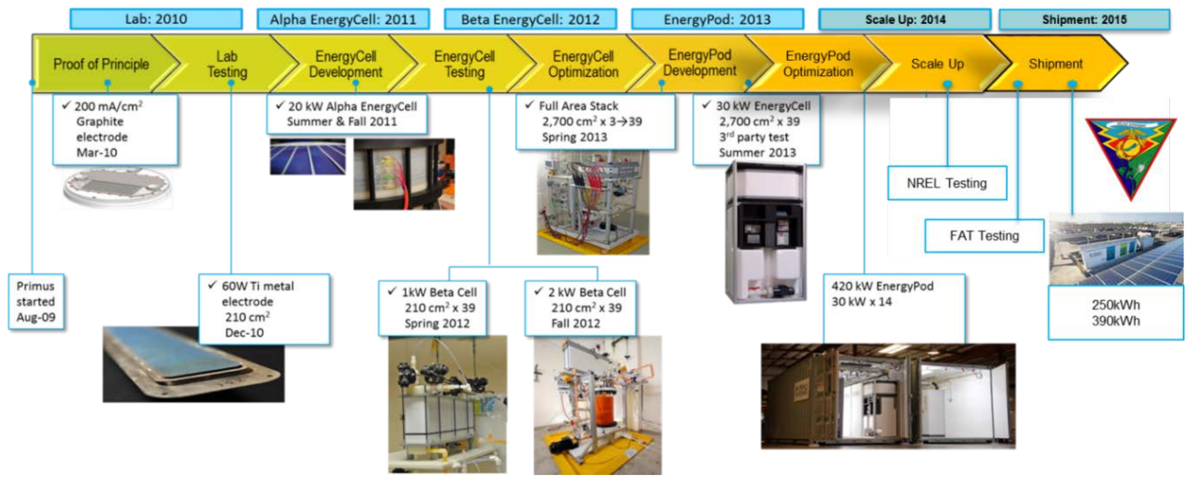

Figure 8. Developmental Timeline for Primus EnergyPod System.

While Primus was working on scaling up and building their first full-scale system in 2014, Raytheon orchestrated hardware-in-the-loop testing of the Miramar microgrid using the National Renewable Energy Laboratory's (NREL) Energy System Integration Facility (ESIF). This effort was funded by Raytheon outside the funding of this ESTCP program; however, the benefits of the NREL testing were heavily leveraged for this program. The intention of the NREL testing was to provide high-fidelity evaluation of Raytheon's IPEM MCS in a simulated operational environment with real hardware-in-the-loop testing including simulated full-scale/full-power sources and loads. The system testing significantly reduced risk integrating the IPEM Controller to manage the existing Advanced Energy PV inverters at MCAS Miramar, the Primus ESS, and the various metering and control logic of the microgrid. The testing at NREL recreated the designed Miramar microgrid at as high a fidelity as possible. Figure 9 shows the one-line diagram for the circuit that was used at NREL's ESIF facility. The NREL system used the same PV inverters as MCAS Miramar, a similar main breaker, and the same inverter and BMS used by Primus' ESS. The results of the NREL testing are summarized in Table 2.

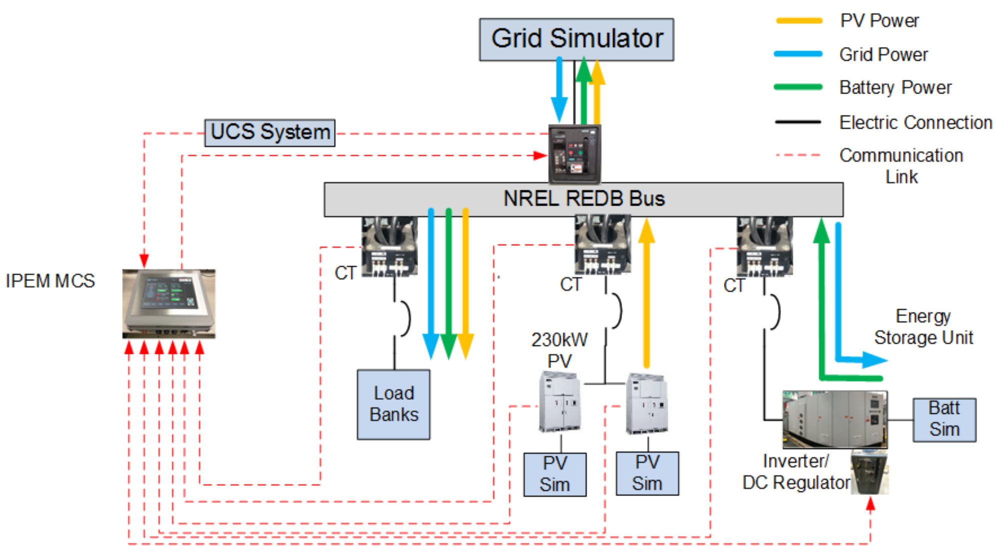

Figure 9. One-line Diagram Design for Test Setup at NREL's ESIF.

Table 2. Summary of Results from NREL Testing.

Goal	Result
The black start sequence and transition to islanding work as anticipated within the 1 hour time requirement	Demonstrated automated black start sequencing
The ESS inverter and PV inverters power share properly in islanding mode	Verified load sharing across operating range (0-200 kW, 0.1-1.0 PF)
The UL1741 anti-islanding algorithms do not destabilize the ESS inverter in voltage control mode	No issues observed
Push PV penetration to >50% without destabilizing the ESS inverter in voltage control mode	Successfully run up to 100% PV penetration (with bi-directional power flow to ESS)
The system does not destabilize due to dynamic PV curtailment and the system can handle load step requirements for Miramar's load	Characterized PV curtailment response timelines in response to increasing and decreasing load changes
The system meets IEEE1547.4 requirements for power quality.	No issues staying within trip points

After completing NREL testing at the end of 2014, Primus was finishing building its full-scale system and by May 2015, they were ready to perform Factory Acceptance Testing (FAT) of the completed ESS at their Hayward facility. The purpose of the FAT was to assess the performance and functionality of the system compared to performance objectives defined in their statement of work (SOW) for the program.

During the course of the ESS build, Primus continuously worked to improve their EnergyCells energy capacity based on the third-party assessment by the SNL testing. At the time of FAT, Primus presented their current state of the energy capacity available with the configuration of EnergyCells that were to be delivered to MCAS Miramar. Figure 10 below shows the progression of meeting the targeted energy capacity as Primus was able to manufacture more of its EnergyCells to populate the system.

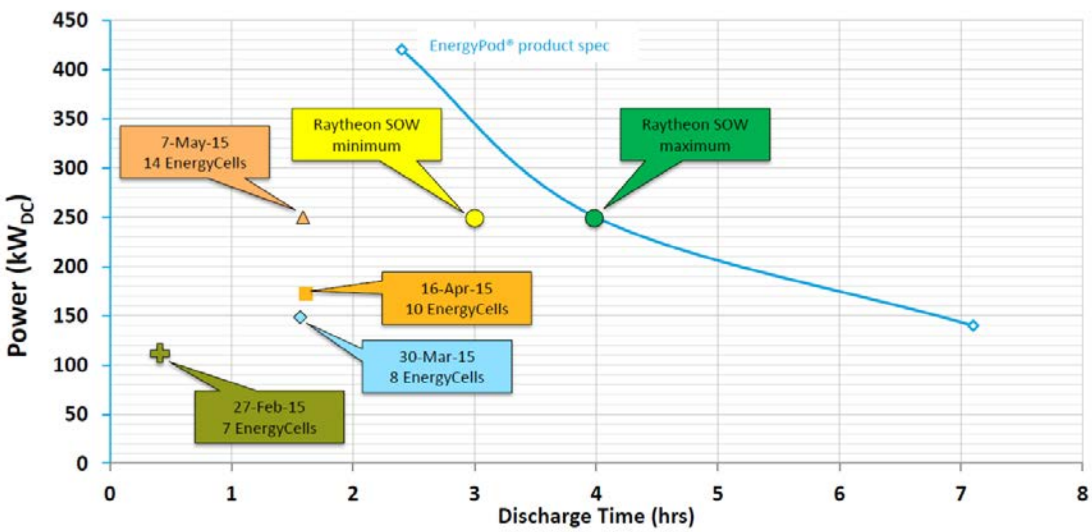

Figure 10. Energy Capacity Timeline and Scale Up from Primus since November 2013 Briefing.

At the conclusion of the FAT, the ESS was demonstrated to be functionally operational though still lacking in the desired energy capacity performance requirement defined in the SOW. At this point in the demonstration, Primus' team had made tremendous progress and investment to get the system to function as required to meet the intent of the program. As the program did not have enough time or resources to increase the energy capacity any further, the system was accepted by Raytheon with agreement and understanding from MCAS Miramar to deliver the system at the end of May 2015.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

Primus' Zn/Br flow battery approach provides advantages in cycle life, cost, and performance when compared to similar technologies. It also offers higher current density, with electrodes that can operate at 200 mA/cm^2 compared to the 50 mA/cm^2 of traditional Zn/Br. Primus' biggest discriminator is that it eliminates two common failure mechanisms in Zn/Br flow batteries (carbon electrodes and separator membranes) by using a solid titanium electrode and not requiring a membrane. This allows their cells to operate longer than traditional flow batteries without the need for replacement. Component-level testing of all of the ancillary equipment and stability testing of their cells have predicted a 20-year lifespan.

Primus' battery still uses a Zn plating mechanism. The nature of the Zn plating requires that the cells be completely discharged to prevent dendrite growth and maintain the health of the cells, meaning that the EnergyCells must be periodically stripped to properly clean and maintain them. This is handled automatically by the BMS within the EnergyPod and is transparent to the end user. However, this requires that an EnergyCell will be periodically taken offline. The ESS will still operate however it will be operating less one EnergyCell reducing its energy and power capacity during those times.

One major limitation of Primus' current system is that when the system is in islanding mode, the ESS operates in voltage control mode and the battery is not capable of charging. This is attributed to adequate control of plating zinc on the electrodes. Primus' development and current algorithms for charging the battery depend on optimal parameters for plating uniform layers of zinc on the electrodes in the EnergyCells. When the system is in islanding mode, controlling the parameters for plating zinc becomes more difficult and Primus has not been able to analyze this functionality to include it in the current operation of the system. Primus' engineers indicated that the capability to charge the system in islanding mode is possible but requires testing the system and validating the techniques, a next step that could not be included in this project due to time and budget constraints.

An additional technical challenge discovered during the implementation of Primus' ESS was the uniformity of the zinc electroplate on the anode of the battery, which ultimately led to a decrease in the total ESS energy capacity. This concern arose while scaling up the Zn/Br technology and proved to be a difficult technical challenge to address due to the state-of-the-art activated solid titanium electrode design. Obtaining a completely uniform zinc plating channel is extremely difficult and results in the electrolyte not discharging at the theoretical rate. Primus is currently investigating this concern and working to implement new methods for uniformly plating the zinc electroplate. However, the issue can be addressed by adding additional EnergyCells to increase energy capacity.

3.0 PERFORMANCE OBJECTIVES

The performance objectives for this demonstration (Table 3), based on early discussion with MCAS Miramar personnel, were established to meet particular mission scenarios for improved energy security and operational cost reductions.

Table 3. Summary of Performance Objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Energy Security Performance Objectives				
Islanding Duration	Time (hours)	Meter readings from RE system, ESS, and grid power feed	Building loads are met by ESS and PV for 72 hours under controlled load conditions meeting power quality standards of IEEE1547.4	Building loads were met by ESS and PV for 5 hours 10 minutes meeting power quality standards of IEEE1547.4; ESS is capable of 7 hours 10 minutes
Building Load Reductions	Delta Average kWh/day usage	Meter readings from building 6311.	Building loads can be reduced by 50% through manual changing of thermostats and lighting when compared to its previous year's average for that given month	Building loads were able to be manually increased and decreased; increased by 68% when compared to baseload during islanding test
Switchover Time	Time (minutes and seconds)	Clock timing from command to go into islanding mode to ESS discharging power	Time is less than hour	Switchover from grid-tied to islanding mode was 4 minutes
Operational Cost Reduction Performance Objectives				
ESS Energy Storage Capacity	Energy Discharged in kWh	Meter reading of energy discharged by ESS	ESS can discharge 1 MWh of energy during peak shaving cycle	ESS was able to discharge 390 kWh in the lab and 290 kWh in the field
Peak Shaving	Peak Demand Reduction (kW)	Meter readings from RE system, ESS, and grid power feed	ESS is able to store energy during off peak time and discharge 250 kW during peak time to reduce peak load relative to historical data over similar time period	ESS was able to store energy during off-peak time and discharge 100 kW during peak time for 2 hours and 45 minutes
Qualitative Performance Objectives				
Ease of Operation	Degree of ease of use	Survey	Satisfactory rating from survey results	Survey to be issued before final report

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4.0 SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The demonstration site at MCAS Miramar is shown in Figure 11. The specific location at MCAS Miramar where the microgrid demonstration occured is near building 6311. Building 6311 is mainly an office building for the energy manager, public works, and Resident Officer in Charge of Construction (ROICC). Since the building houses the energy manager and staff, the ability to take the building offline during the islanding scenarios was easier to facilitate. The base command endorsed the project as a major stepping stone to achieving a larger microgrid effort and was very accommodating when scheduling outages to the integrated system and performing demonstrations.

The project's data communications were designed to be a closed loop system avoiding any Department of Defense Information Assurance Certification and Accreditation Process Risk Management Framework (DIACAP/RMF) and information technology (IT) platform certifications. The data that was collected within the IPEM Controller and the ESS was stored locally at Miramar and could be downloaded on the base and transferred for analysis.

Figure 11. Map and Aerial Image of MCAS Miramar.

4.2 FACILITY/SITE CONDITIONS

MCAS Miramar is located in a mild climate zone in southern California. The location provides good solar irradiance for the installed PV systems. Building 6311 was a perfect location for this demonstration since it has its own switchgear with 230 kW of PV attached to it. The switchgear allowed isolation of the circuit for islanding, and the PV system allowed the integration of renewable energy into the circuit when operating in islanding mode.

Many southwestern installations have large amounts of PV installed on their facilities and many are subject to similar IAs and UL1741 anti-islanding restrictions. This demonstration at MCAS Miramar helped prove the concept of using energy storage in a microgrid application for integrating RE systems when in islanding mode.

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5.0 TEST DESIGN

This goal of this demonstration was to solve two main problems. The first problem was that DoD facilities are vulnerable to grid outages due to extreme events and are limited to non-renewable back-up systems such as diesel generators, which are regulated and cannot be used for cost reduction applications such as peak shaving. The second problem was that the peak electrical loads of many DoD facilities occur during high rate periods, incurring significant costs associated with demand charges. The demonstration aimed to answer the question: "How can an ESS, coupled with an advanced control system, provide energy security while reducing overall facility energy costs?"

5.1 CONCEPTUAL TEST DESIGN

The Zn/Br installation consisted of a Zn/Br ESS integrated into the MCAS Miramar utility infrastructure, which included a 230-kW carport PV subsystem and a 30-kW rooftop PV subsystem. The ESS and the PV subsystems were controlled by the IPEM MCS, which also controls and monitors the load demand and power quality required by the MCAS infrastructure, the status and power generation of the PV system, and the state of health of the ESS (Figure 12).

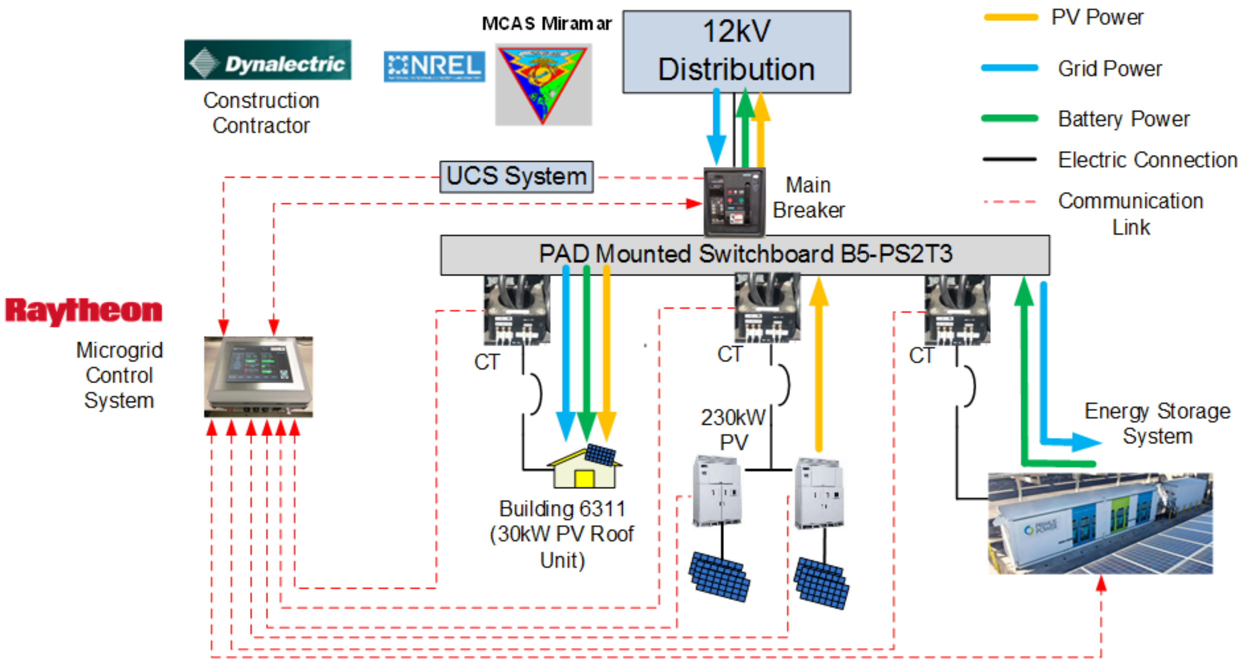

Figure 12. Interconnect Diagram of Zn/Br Installation at MCAS Miramar.

The demonstration was designed to operate in two modes: 1) islanding and 2) peak shaving. The islanding mode demonstrated the energy security performance objectives and the peak shaving mode demonstrated the operational cost reduction performance objectives.

The primary mission for the Zn/Br installation was to provide emergency power in the case of a grid outage. Maximizing the use of the PV system and the ESS is crucial to extend the operational life of the system. This allows MCAS Miramar to operate independently from the grid in the case of a physical/cyber attack or an environmental event that would otherwise shut down facility power.

The system is connected to a 230 kW PV system that currently exists on the B5-PS2T3 switchgear. The carport PV inverters are UL1741-certified and therefore have built-in safety features that de-energize the inverters during a grid outage. To meet duration goals in islanding mode, these inverters needed to be active to supplement the Zn/Br battery in providing power to the MCAS Miramar load. To accomplish this, the PV inverters require a firm voltage source to activate and synchronize. The ESS provided this voltage source for the islanding system, maintaining voltage regulation of the circuit. During this mode, the circuit is isolated from the rest of MCAS Miramar's distribution system with the installation of a remote-operated main breaker at the point of common coupling (PCC), which replaced the pre-existing main breaker on the B5-PS2T3 switchgear. The main breaker opens and closes based on commands from the IPEM Controller to isolate the circuit from the grid, thereby meeting the guidance referenced in IEEE1547.4. Since the ESS acts as the voltage regulator for the system, it cannot charge while in islanding mode as part of its current control software. Precise control of the zinc plating process is required for the energy cells to operate efficiently. Primus had not fully developed the control systems and algorithms to monitor and maintain uniform zinc plating that switches from charge to discharge quickly when operating in voltage control mode. While the basic principle of rapid discharge and charge has been demonstrated in their lab, the software and real-time controller code had not been developed at the time of the demonstration and was therefore a limitation of the system used in this demonstration.

Because the ESS did not currently have the capability to charge when operating in voltage control mode and the PV system generates more than the building load, the 230 kW PV subsystem needed to be controlled to make sure that more power than required during islanding mode was not generated. Typical commercial PV inverters are not capable of being actively curtailed, however the two Advanced Energy (AE) inverters that are part of the 230 kW PV subsystem were able to be enhanced to provide this capability. Raytheon collaborated with AE to develop a software update to the two PV inverters, and the upgraded PV inverter communication cards and firmware provided the capability to remotely curtail the PV power output in a subcycle timeframe via a Modbus interface.

During islanding operation, the IPEM Controller modulated the curtailment set point of the PV inverters to keep the power generated by the PV below the demand required by the building. The ESS provided the remaining power delta between what the PV generated and the power required to meet the load. Data taken during the demonstration showing this behavior is shown in Figure 13 below.

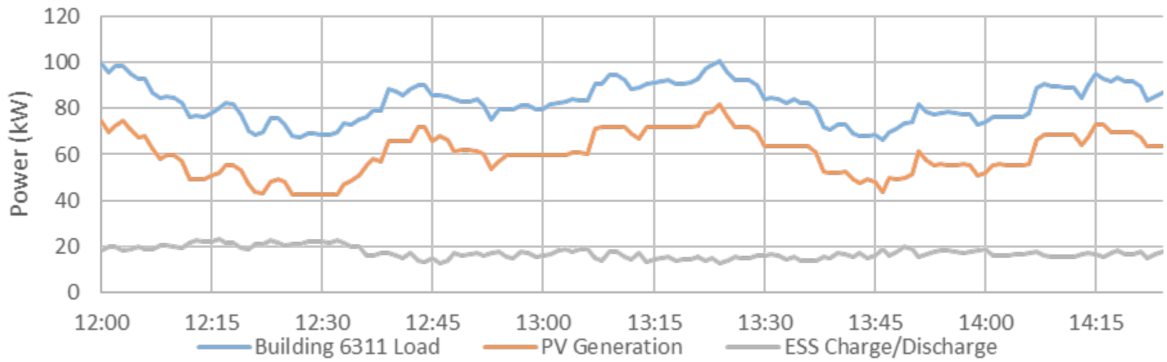

Figure 13. Load and Power Output Profile for the Zn/Br Installation during Islanding Operation Showing the Curtailment Functionality of the PV Inverter Controlled by the IPEM Controller.

The blue line shows the load profile of the building circuit while in islanding mode. The orange line shows the controlled power output of the PV inverters when managed by the IPEM Controller. The power output is controlled (or curtailed) to always remain below the load while the ESS provides the remaining power needed. Prior to starting the program, the amount that the PV inverters would need to be curtailed was unknown, as it was dependent on the capabilities of the power electronics within the ESS, the IPEM Controller, the response time of the AE inverters, and the behavior of the MCAS Miramar load. Each one of these elements required detailed modelling, analysis, and testing to validate the proper functional behavior required to make them work together.

To design the system properly, the load profile for MCAS Miramar needed to be understood. The load profile for Building 6311 at MCAS Miramar consists of both real and reactive power components. The reactive component of the MCAS Miramar load is mainly due to motor loads from its heating, ventilation, and air conditioning (HVAC) systems. A plot of Building 6311's load profile, including the real and reactive power components, is shown in Figure 14.

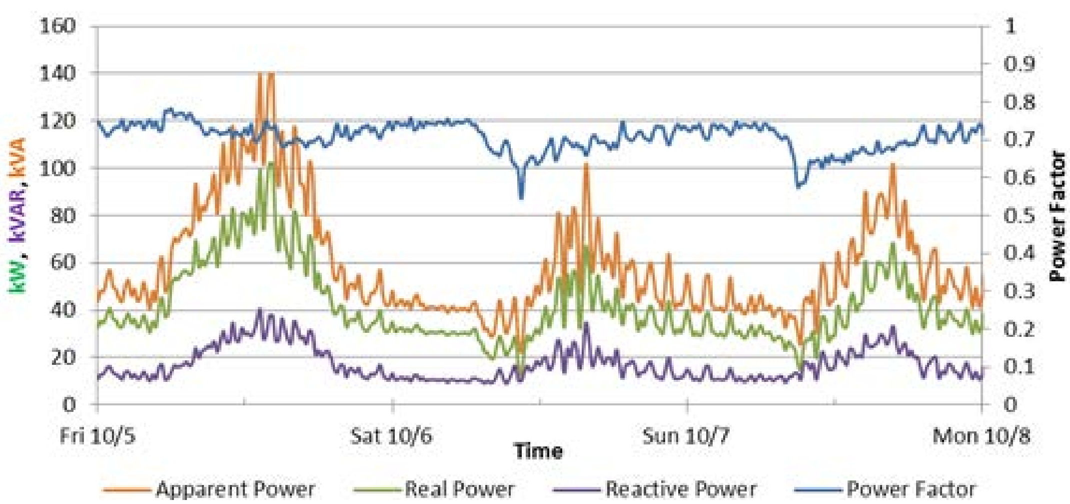

Figure 14. Load Profile for Building 6311 Including Real, Reactive, and Apparent Power as a Function of Time.

The data was sampled at 15-minute intervals. The power factor is plotted on the secondary axis.

Because the load consisted of a reactive power component, power factor (PF) needed to be taken into consideration when managing the PV load. The AE inverters can only source real power, so the ESS needed to source all required reactive power while operating in islanding mode. This capability within the ESS power electronics was tested during the NREL ESIF tests. The variable nature of PV production and motor loads also creates transient conditions that required accommodation by the power electronics of the ESS. Therefore, the amount of PV power provided to the load needed to be balanced between the capabilities of the ESS power electronics and the transient conditions of the circuit. During the course of developing and testing the system, it was determined that the power electronics within ESS require approximately 10 kW of consistent power output to maintain the control loops that manage the battery's direct current (DC) bus.

The demonstration also illustrated the second mode, the capability for an ESS to allow a facility to reduce peaks in power usage by implementing peak shaving algorithms. A controlled charge and discharge of the ESS according to a programmed or automated schedule results in a load profile of grid purchases changed in favor of the facility to avoid peak demand and transmission charges. An example of this is shown in Figure 15.

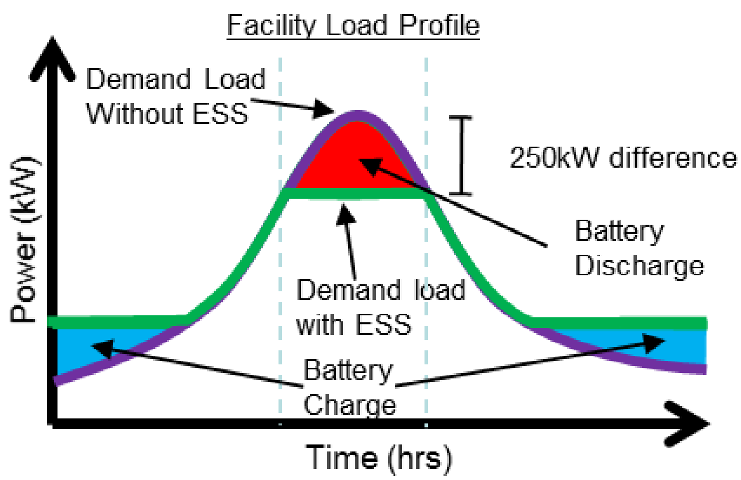

Figure 15. Plot Showing How Peak Shaving Can Change the Load Profile of a Facility as Seen by the Utility.

5.2 BASELINE CHARACTERIZATION

The baseline characterization of MCAS Miramar's Building 6311 was taken in November 2015, prior to the December demonstration (Figure 16). The data was collected from the Advanced Metering Infrastructure (AMI) smart meters that are installed in the B5-PS2T3 switchgear.

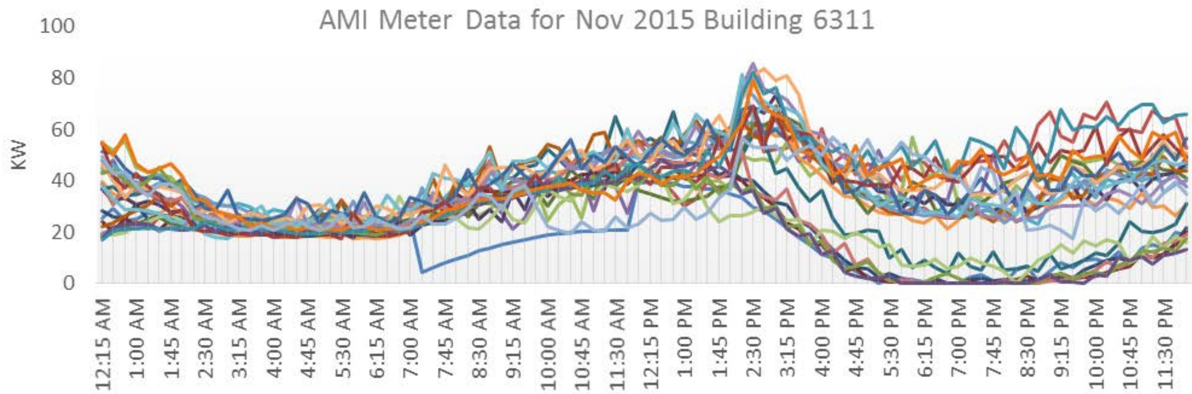

Figure 16. Daily Load Profiles for Building 6311 during November 2015.

Each color represents a different day in the month of November.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

This demonstration consisted of four significant technology elements: 1) the Zn/Br ESS, 2) the IPEM MCS, 3) the B5-PS2T3 switchgear, and 4) the PV inverters. The locations and layouts of each element are shown in Figure 17 below.

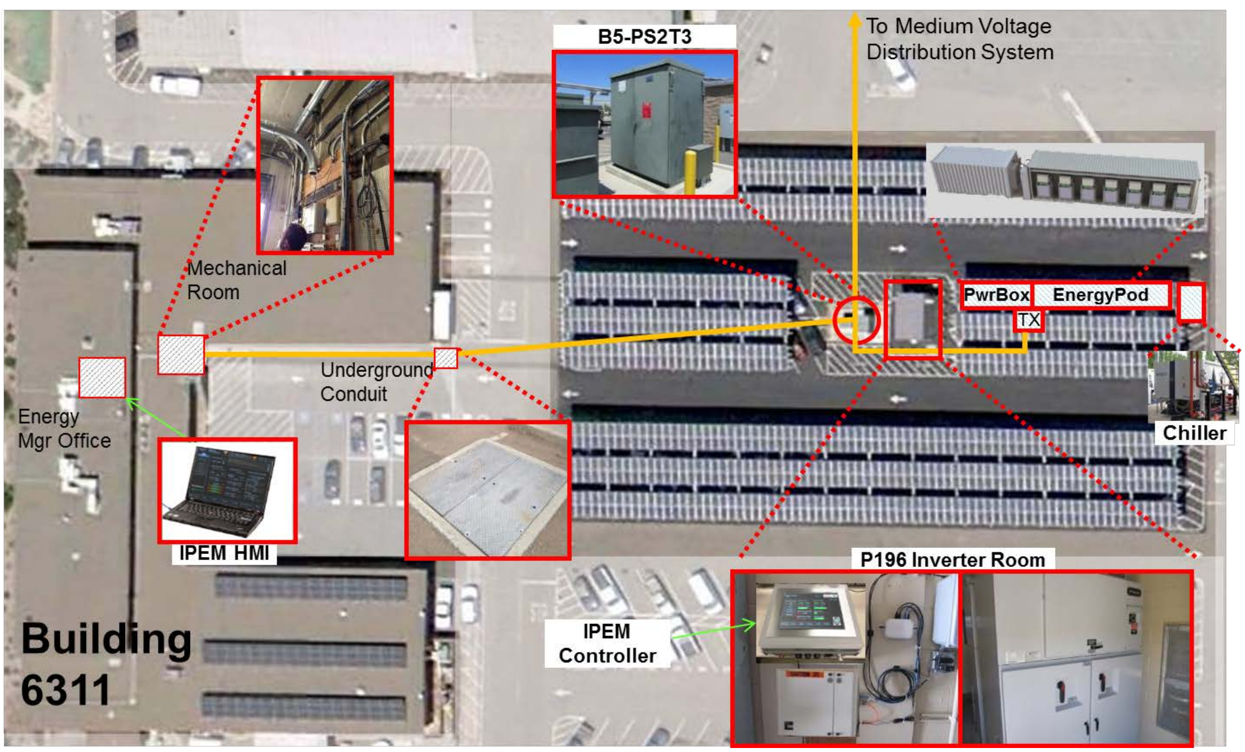

Figure 17. Bird's Eye View of MCAS Miramar Site and Layout of System Components Outside Building 6311.

The orange line represents electrical connections.

5.4 OPERATIONAL TESTING

Testing of the microgrid, including the demonstrations, was divided into three phases of test: 1) system initialization and checkout, 2) grid-tied mode, and 3) islanding mode. Each phase of testing is described in more detail below and the dates for the fielded demonstrations are shown in Table 4 below.

5.4.1 System Initialization and Checkout

System Initialization and Checkout consisted of installation, interconnection (power and communication), and verification of operation and communication of the equipment prior to demonstration start.

5.4.2 Grid-Tied Mode

The grid-tied testing was intended to demonstrate that the system was properly configured and functionally capable of meeting the peak shaving and energy storage capacity performance objectives.

Grid-tied mode testing achieved the following objectives:

1) Verified integrated system functionality and monitoring/fault detection functions of the IPEM MCS in the presence of real PV source and load characteristics
2) Validated scheduled peak shaving functionality in grid-tied mode in the presence of real PV source and load characteristics

5.4.3 Islanding mode

Islanding mode testing was intended to demonstrate that the system was properly configured and capable of meeting the islanding duration, building load reductions, and switchover time performance objectives.

Table 4. Dates and Durations of the Field Demonstrations for the Grid-tied and Islanding Mode Testing.

Test Phase	Test	Date	Duration
Islanding mode	Islanding Operation Battery Only Isolated from Circuit (Self Powered)	10/23/15 10/24/15 10/25/15	1 hour 1 hour 1 hour
Islanding mode	Pre-Island Conditions	10/24/15	3 days
Islanding mode	Island Transition Test	10/24/15	1 day
Grid-tied Mode	Energy Storage Capacity	11/15/15 11/17/15	1 day 1 day
Islanding mode	Intentional Islanding with PV Tests	12/12/15 12/13/15	1 day 1 day
Grid-tied Mode	Baseline Data Collection	12/29/15	1 day
Grid-tied Mode	Peak Shaving	1/12/16	1 day

5.5 SAMPLING PROTOCOL

The sampling protocol during the various operational tests and the demonstration are described below.

Data Description

- Sample Rate = (1–5 second intervals for IPEM Controller, sub-second intervals for power analyzers)
- Grid input
- PV power output and quality
- Building load and quality (PF, Crest Factor (CF))
- ESS power level and direction (charges vs. discharge)
- Data transmission (to and from IPEM, ESS, PV inverter)
- Response time

Data Collector(s)

- Raytheon and NREL personnel

Data Recording.

- Automated:
  - The IPEM Control unit will log all variables in its internal database
  - Calibrated Power measurement equipment will be used to validate the IPEM data (Fluke 437 and Fluke 1735)

Data Storage and Backup

- IPEM Controller employs built in flash memory which will store all collected data
- Remote monitoring data storage unit
- Fluke power analyzers have removable flash memory that collects sub-second power quality data

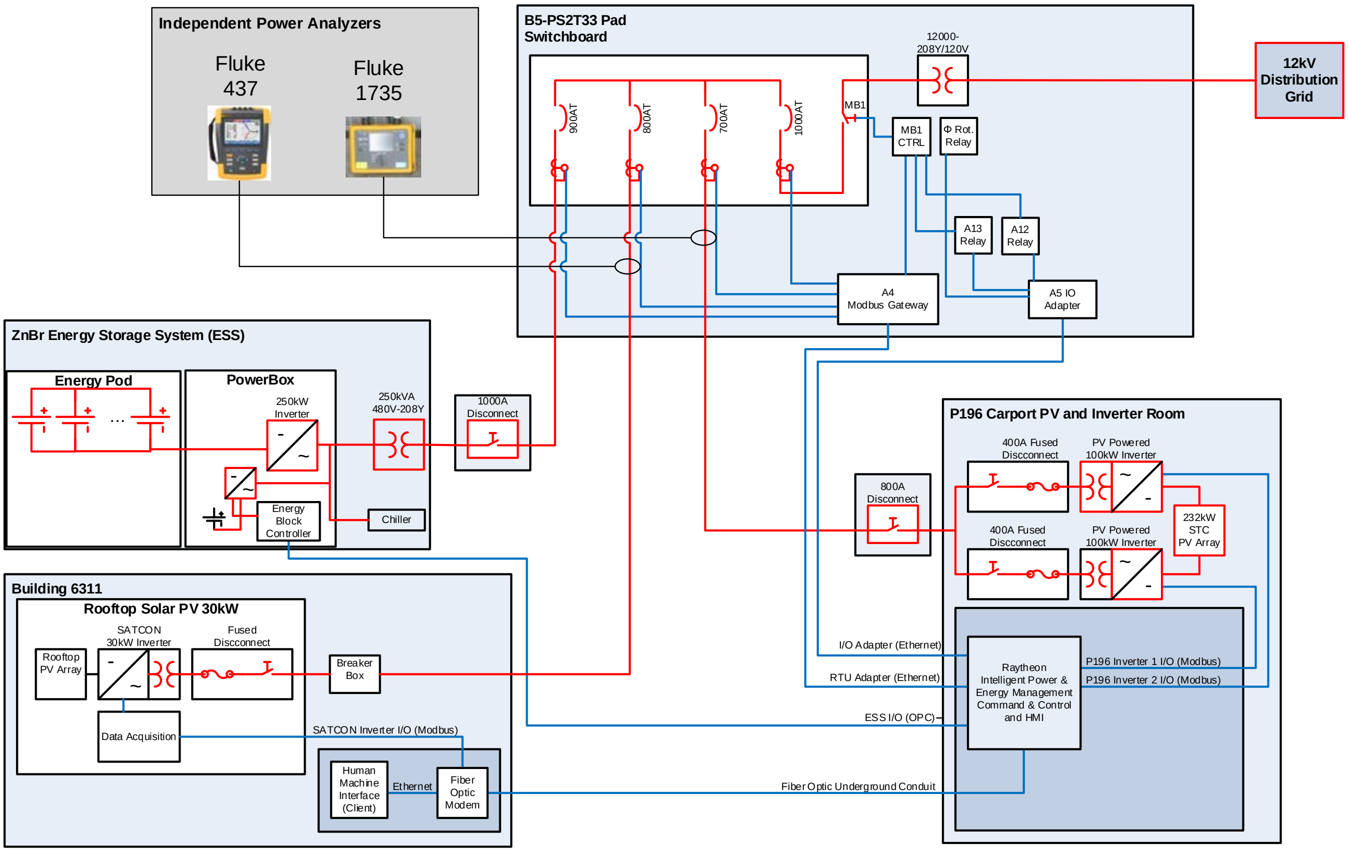

Figure 18. Detailed Schematic of the Interconnection of the Various Subsystem Components of the Installation.

5.6 SAMPLING RESULTS

This demonstration collected gigabytes of detailed load data that are summarized in the performance assessment section of the Final Report. Detailed graphs are shown from the December 13, 2015, islanding demonstration in Figure 19, Figure 20, and Figure 21 below.

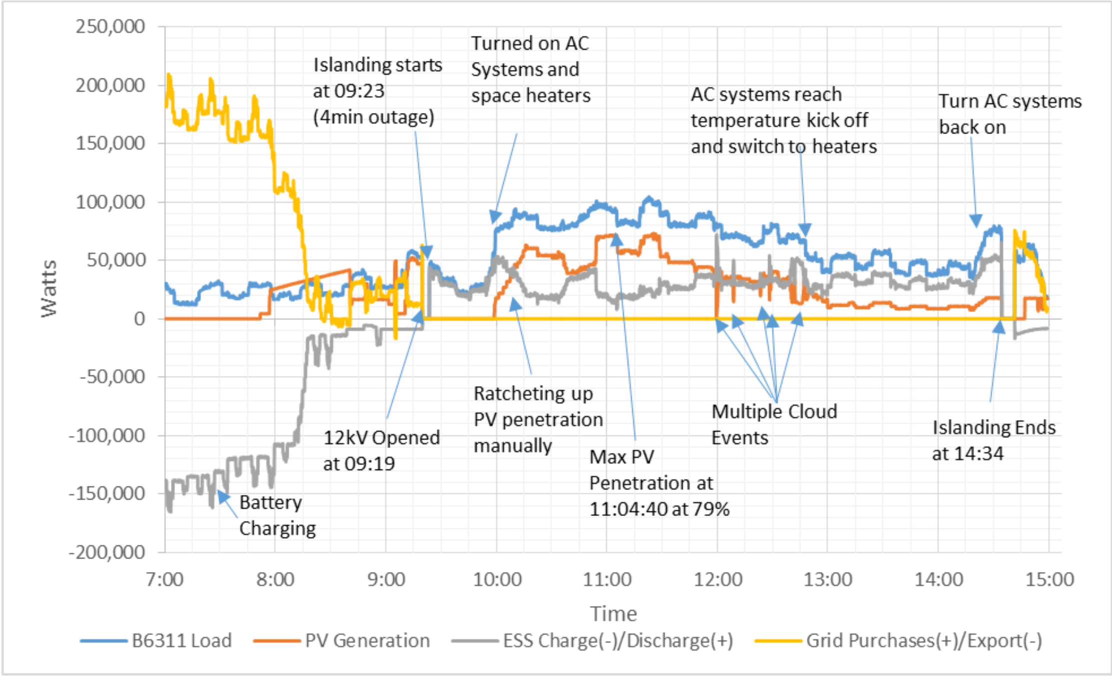

Figure 19. Summary Load and Generation Profile during 12/13/15 Islanding Mode Demonstration Test.

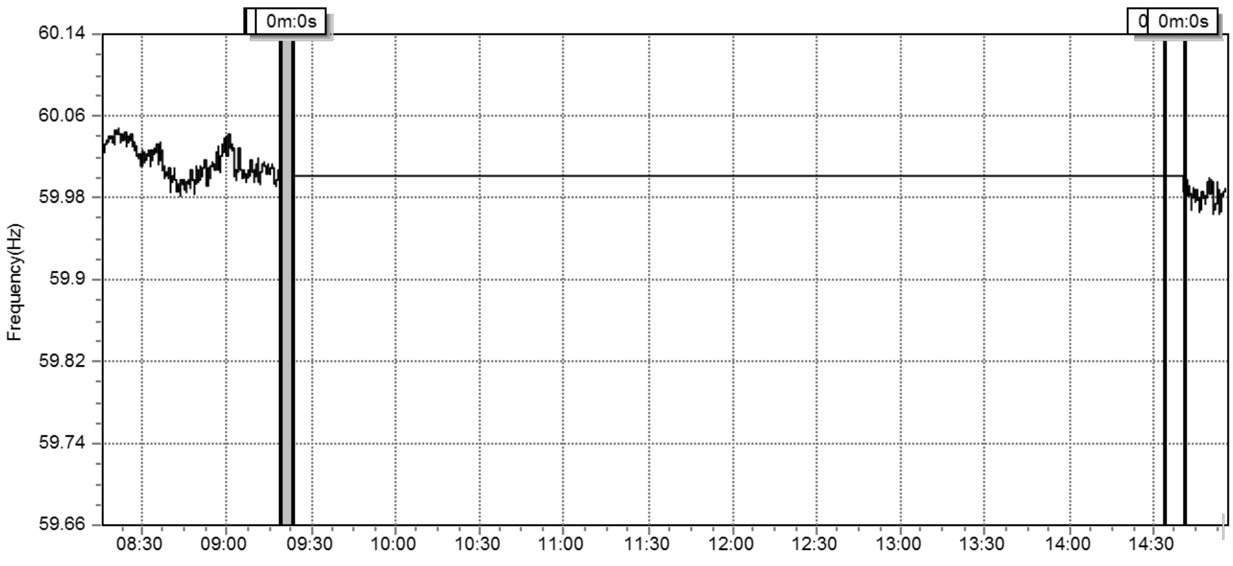

Figure 20. Frequency Measurements during 12/13/15 Islanding Mode Demonstration Test.

Data was taken from Fluke 437 power analyzer. Frequency was maintained at a very stable 60 hz.

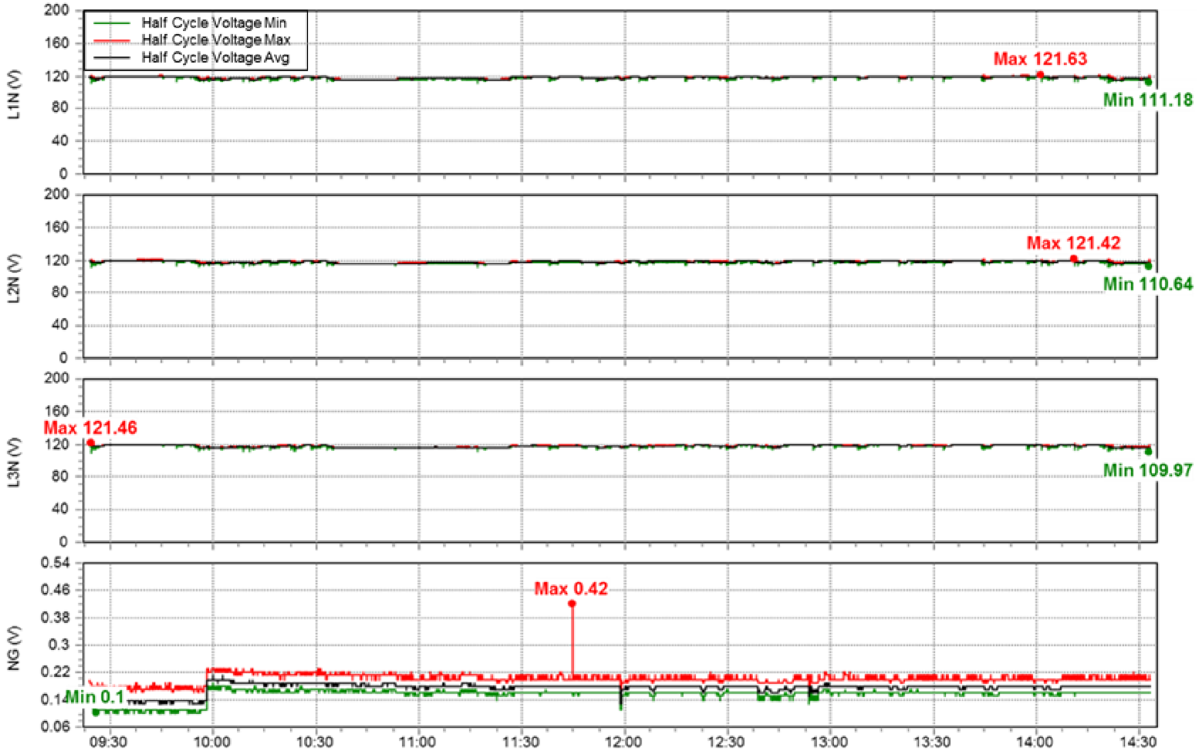

Figure 21. Phase-to-phase Voltage Data during 12/13/15 Islanding Mode Demonstration Test.

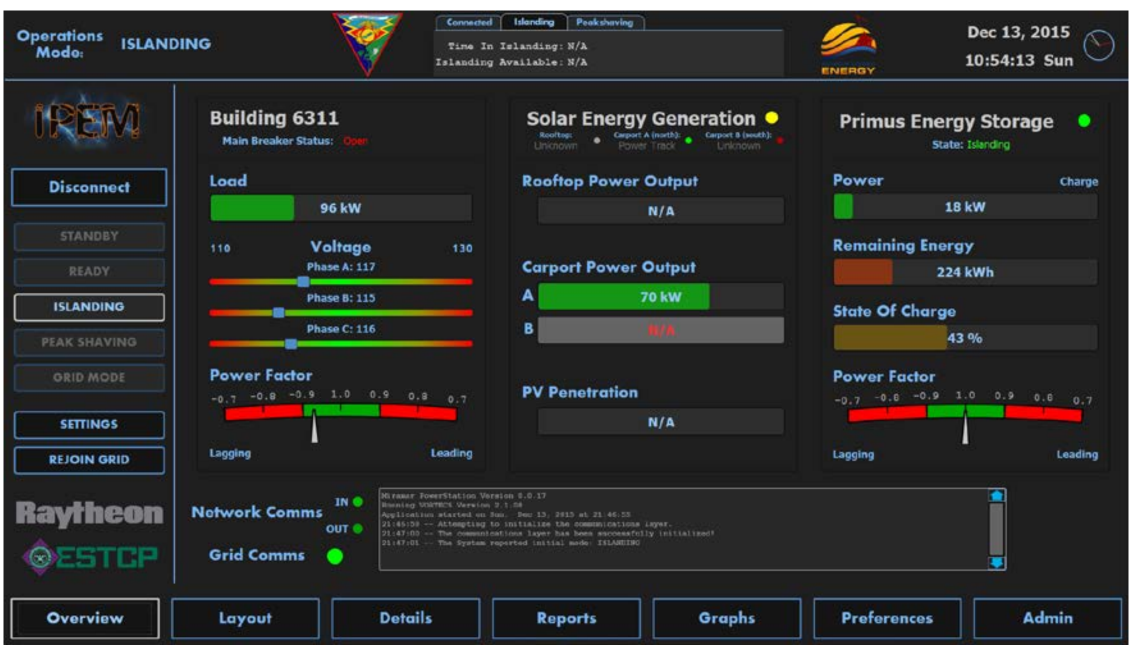

Figure 22. Screenshot of the IPEM HMI during the 12/13/15 Islanding Event.

This screenshot shows the status of each of the subsystems in islanding mode. At this time (10:54) the PV power is providing ~73% of the load.

6.0 PERFORMANCE ASSESSMENT

6.1 ISLANDED DURATION

The success criteria for this performance objective was that building loads would be met by the ESS and PV system for at least 72 hours under controlled load conditions meeting power quality standards of IEEE1547.4. During the final demonstration tests on December 13, 2015, the system was able to successfully island for 5 hours and 10 minutes. The data was analyzed to determine if the quality of power met IEEE1547.4 guidelines. The IEEE1547.4 document describes many guidelines for meeting the load conditions for the microgrid and is dependent on fully understanding the existing load conditions that the microgrid will need to maintain. Ranges for meeting power quality standards are contained in American National Standards Institute, Inc./National Electrical Manufacturers Association (ANSI/NEMA) C84.1-2006 and referenced in IEEE1547.4. A summary of the important requirements listed in IEEE1547.4 are shown in Table 5 along with the description of compliance based on data collected during islanding testing.

Table 5. Summarized IEEE1547.4 Requirements Pertinent to ESTCP Demonstration.

1547.4 Par. No	Requirement Description	Compliance Description
4.2	The planned DR island system shall maintain voltage and frequency for the entire island system including the non-participating DR systems and loads.	Voltage and frequency were maintained to ANSI/NEMA C84.1-2006 ranges.
4.2	In a planned island, loads shall be balanced for each phase. [Calculation for voltage balance is in C84.1 -2006 and should limit unbalance to 3%. Example: with phase-to-phase voltages of 230, 232, and 225, the average is 229; the maximum deviation from average is 4; and the percent unbalance is (100 X 4)/229 = 1. 75 percent.]	L1 Ave = 118 L2 Ave = 118 L3 Ave = 118 Max Deviation from Ave = 0 (100x0)/118 = 0
5.1.2	The reactive power requirements of the DR island system during the island condition are important to consider. DR shall support real and reactive load requirements at an acceptable voltage level. The reactive power requirements of the load during island conditions needs to be understood in relation to the real power requirements of the load and the DR island reactive power resources.	Voltages were maintained within ANSI/NEMA C84.1-2006 ranges under reactive power conditions.
5.1.2	Reactive power resources shall be sufficient not only to address steady-state reactive power demands, but also to address dynamic reactive power demands, such as those related to motor starting within the DR island system. There are possible interactions between the customer's and area EPS's power factor correction equipment and synchronous motors and DR. There needs to be sufficient reactive power resources available when operating induction or some inverter-based DR.	The ESS provided sufficient reactive power to address dynamic reactive power demands. HVAC units were utilized to create reactive power loads.
5.1.4	DR island systems shall be capable of starting and maintaining motor operations. Motor-starting inrush current can exacerbate voltage drops in the DR island system. This voltage drop may result in a degraded ability to start the motor or cause loss of generation. Extended motor acceleration times may cause excess heating, which may reduce motor life and may cause motor overcurrent protective devices to operate. Soft- start controllers or reduced voltage starters on large motors can reduce inrush currents and thus minimize their impacts.	HVAC units within Building 6311 were turned on repeatedly during testing to create motor-starting inrush currents. The ESS was able to meet these loads while maintaining voltage levels per ANSI/NEMA C84.1-2006.

Table 5. Summarized IEEE1547.4 Requirements Pertinent to ESTCP Demonstration (Continued)

1547.4 Par. No	Requirement Description	Compliance Description
4.4.3	The DR island system shall provide the real and reactive power requirements of the loads within the island and serve the range of load operating conditions. [Using Building 6311 Load Data]	Variable load conditions were created during islanding tests and they were all met.
4.4.3 & 6.1	The DR island system shall actively regulate voltage and frequency within the agreed upon ranges (e.g., as specified in ANSI/NEMA C84.1-2006 for DR island systems that include the area EPS). Voltage regulation equipment within the DR island system may need to be modified to meet the needs of the DR island system. [184Y/106V to 220Y/127V, 59.3 Hz to 60.5 Hz]	L1 Vmax = 121.63 / L1 Vmin = 111/18 L2 Vmax = 121.42 / L2 Vmin = 110.64 L3 Vmax = 121.46 / L3 Vmin = 109.97
4.4.3	During the island mode condition, transient stability shall be maintained for load steps, DR unit outage, and island faults.	Transient load steps were created with HVAC units as well as PV sources turning off during tests. The system maintained power quality throughout the demonstration.
4.4.3	If there are multiple DR units in the DR island system, their operation shall be managed and coordinated to effectively meet the needs of the island.	Both ESS and PV power were utilized in the islanding demonstration. The PV and ESS were coordinated by the IPEM controller adequately during the test.
4.4.4	Once the DR island system is paralleled to the area EPS, all DR shall return to IEEE 1547 compliance within area EPS time requirements. [1 hour in the Demo Plan]	The goal for the project was to re-connect the system within 1 hour and this was achieved during the testing.

After post-processing the data collected and further investigation, it was concluded that there was energy capacity still remaining in the ESS when the system exited islanding mode. This was supported by voltage measurements collected on the DC string voltage in the ESS and the DC power injected into the Parker Inverter. It was determined that the reason the battery went into inactive mode at the end of islanding mode testing was because there was a power supply failure in one of the control boxes of an EnergyCell. This resulted in the loss of gate power to one of the H-bridges which triggered a fast fault in the ESS, causing the central regulator to ramp itself down and set the battery in inactive mode. Therefore, the ESS discharged ~159 kWh of energy during the December 13, 2015, islanding mode demonstration. The ESS has been calculated to have ~290 kWh of energy capacity based on the energy capacity tests. This would have left ~131 kWh of energy remaining in the ESS. The average load from Building 6311 was ~64 kW during the islanding demonstration, meaning that the islanding mode demonstration should have been able to run for another 2 hours at the average 64 kW load. This would have put the islanding duration at a theoretical 7 hours and 10 minutes for those load conditions.

6.2 BUILDING LOAD REDUCTIONS

The success criteria for this objective was that building loads could be reduced by 50% through manual changing of thermostats and lighting. Building load reduction capability was calculated to be 68% from manual changing of thermostats and Direct Digital Controller (DDC) set points during the islanding testing. Figure 23 depicts the data showing the increased manual load steps.

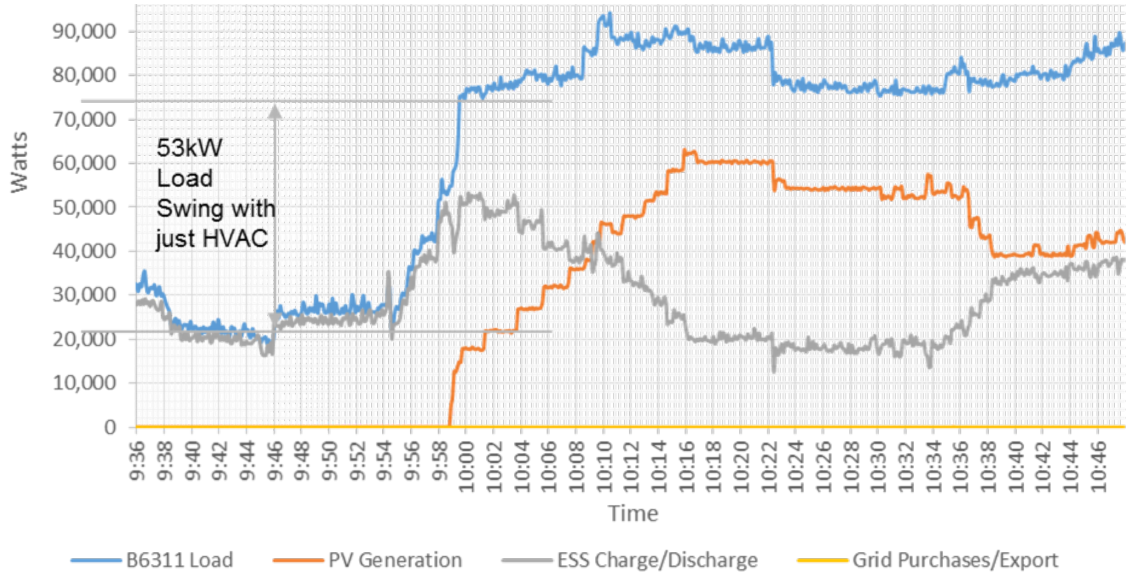

Figure 23. Load Profile from 12/13/15 Islanding Mode Demonstration Test Highlighting Load Steps from Manually Increasing HVAC and Building Loads.

6.3 SWITCHOVER TIME

Switchover time is the time from when the system is commanded to enter islanding mode to the time power is restored to Building 6311 by the microgrid. The success criteria for this performance objective was defined as less than 1 hour. During the December 13, 2015, islanding mode demonstration test, the time the system took to transition into islanding mode was recorded at 3 minutes and 47 seconds. When the islanding event was over and the system needed to restore grid power, it took the system 7 minutes and 1 second to re-connect to the grid. The timeline for switching the system into islanding mode starts when the system is commanded via the IPEM HMI to enter islanding. The IPEM controller disables the PV inverters, sets the ESS to standby, checks the safety interlocks within the switchgear, and then opens the main breaker. The IPEM controller then commands the ESS to enter an islanding state. This reboots the Parker Inverter within the ESS in voltage control mode, which takes under a minute. Once booted successfully the ESS starts to ramp up the voltage on the DC bus. This takes a couple minutes for each EnergyCell to be added to the EnergyPod's DC bus. Once the DC bus is above 600 V, the Parker Inverter closes its Alternating Current (AC) breaker and power is provided to the microgrid. To switching out of islanding mode, the system is restored to grid power via the IPEM HMI. Once initiated, the IPEM controller then disables the ESS and PV inverters if they are still running; if not, it sets them to standby while they are in backup power mode. The IPEM controller then checks the status of the base grid to see if it is active through a phase rotation relay located inside the switchgear. If the grid is present and everything is in standby, IPEM closes the main breaker, thereby restoring power to the building.

6.4 PEAK SHAVING

There are two pieces of data required to calculate the peak shaving metric. The first is relevant historical load profile data, which was collected a couple days prior to using the ESS in peak shaving mode and is shown in Figure 24.

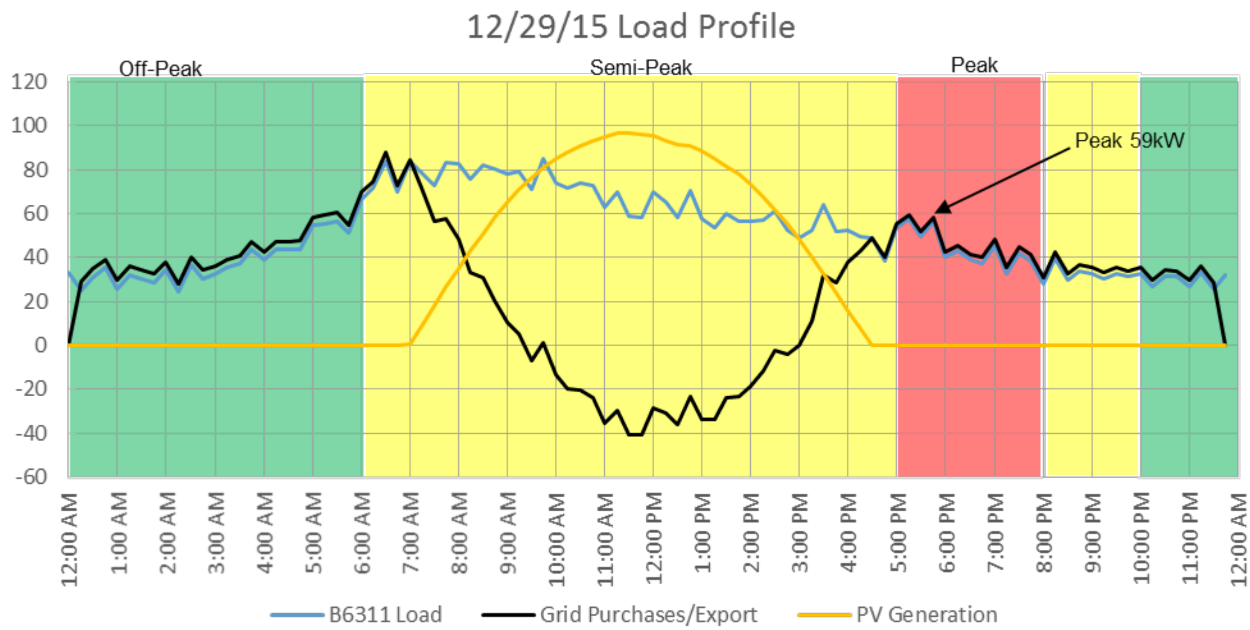

Figure 24. Baseline Load Profile of Building 6311.

The black line represents what demand is seen by the meter that calculates demand charge. The red area in the graph is the time when peak demand charges are calculated.

The second piece of data is the load profile when using the ESS in its peak shaving mode. The metering points for the load were collected at the B5-PS2T3 switchgear according to the Current Transducer (CT) locations defined in Figure 12. The load data collected is summarized and shown in Figure 25 below.

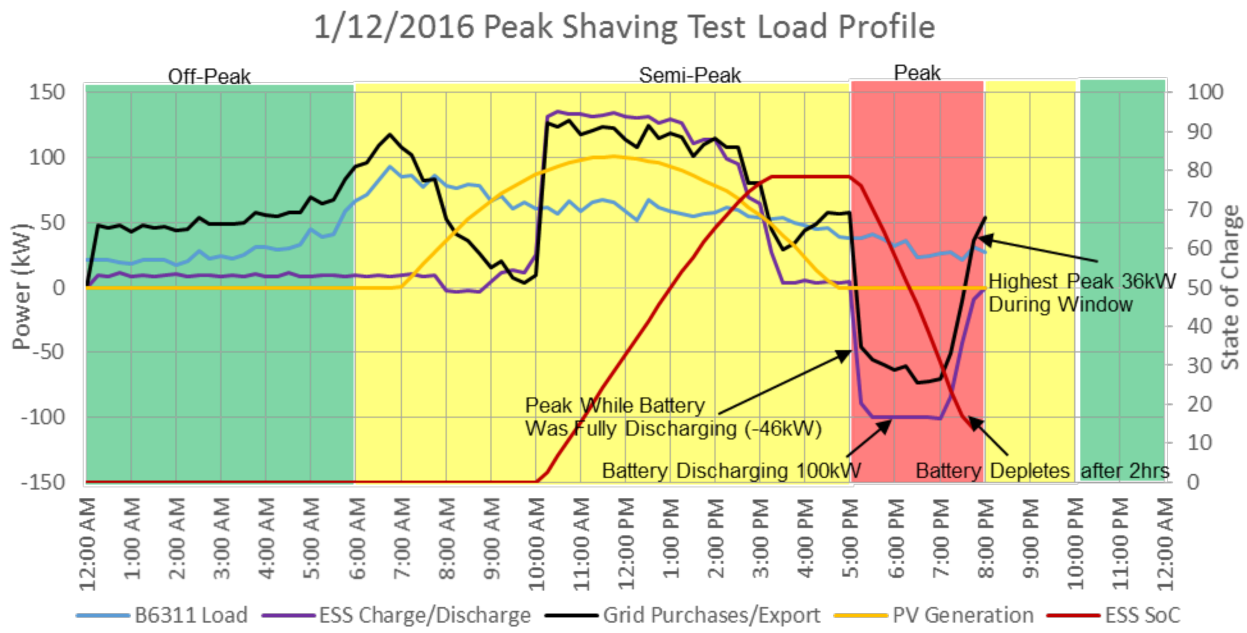

Figure 25. Peak Shaving Test Data Taken on 1/12/16.

The battery is discharged at 100 kW starting at 5:00PM. The black line changes to negative during the red peak time while the battery is discharging. The battery depletes before the peak time period is over and the black line rises right before 8:00PM.

Both the historical load data and load data used in peak shaving mode are compared to each other to quantify the peak shaving difference achieved.

The success criteria for this metric was originally determined to be the ESS' ability to store energy during off peak time and discharge 250 kW during peak time to reduce peak load relative to historical data over similar time period.

Based on the energy capacity available in the ESS installed at MCAS Miramar and that it was desired that the demonstration perform against SDG&E's winter time of use (TOU) peak time period it was determined that the ESS should be set to discharge at 100 kW power output to achieve three hours of required discharge. During the test, the battery started discharging at 5:00PM at 100 kW and was able to change the profile of the grid purchases at the main feeder metering point to export 46 kW of power into the distribution system. At approximately 7:00PM, after two hours of discharging the battery started approaching 30% state of charge and the total output power of the battery started to diminish less than 100 kW and slowly lessened until the battery was unable to provide power any longer just before 8:00PM. The end result showed that the battery was capable of peak shaving at 100 kW for just under the three hours, but not long enough to get through the whole peak time period of three hours. The ESS would need to be set to a lower power discharge output to get through the entire peak TOU period.

The data was then compared to the baseline data collected prior to conducting the peak shaving. Figure 26 below shows the comparison of the two load profiles. The two load profiles show similar load characteristics. The base load of the circuit operates between 30–50kW. As people get to work in the morning (6:00AM) in Building 6311, there is an uptick in load on the circuit as lights are turned on an people start their workday. Sunrise in December/January at MCAS Miramar was between 6:45AM–7:00AM and it is shown that the load starts dropping as the PV systems start to generate power. The real differences occur at 10:00AM when, during the peak shaving test, the ESS was set to charge resulting in a sudden ramp in load on the blue line. At approximately 3:25PM, the charge was stopped and the ESS dwelled at until 4:50PM, when the ESS was set to discharge at 100 kW output. From here, the delta between the two load profiles is shown to be 105 kW, validating the 100 kW capability of reducing demand during peak time. At 7:00PM the battery started to reduce its power output as it neared the lower end of its state of charge, causing the grid load to rapidly increase until the battery was fully depleted at approximately 8:00PM. This shows that the output power of the battery would need to be reduced in order to discharge for the full three hours.

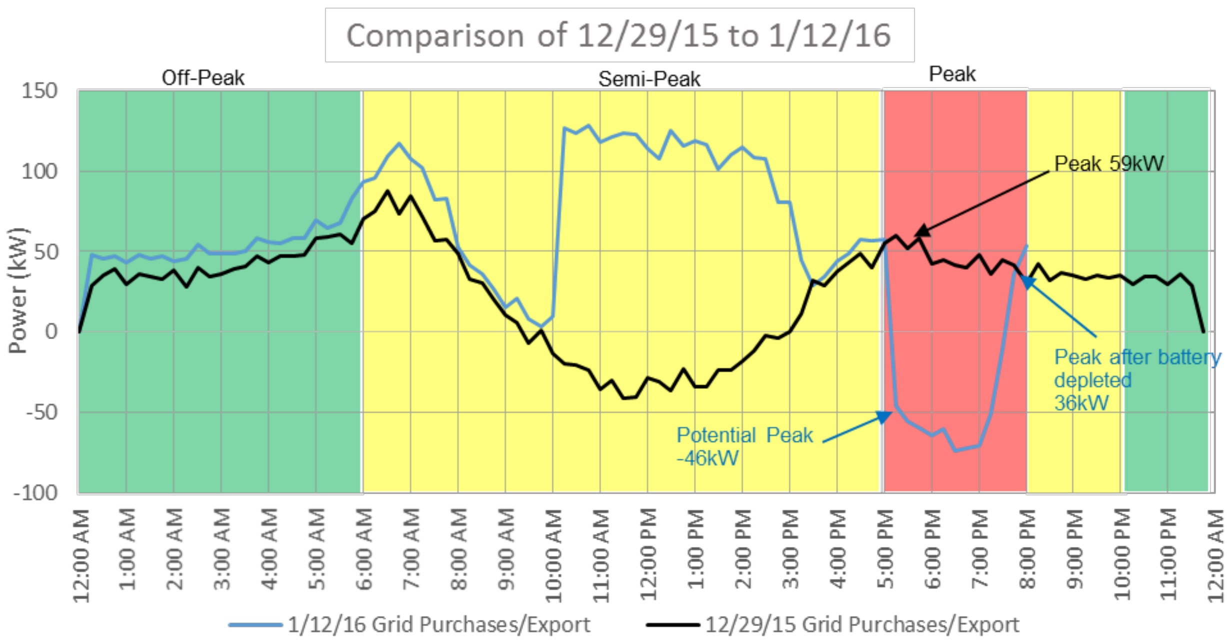

Figure 26. Comparison of the Load Data Collected on 12/29/15 to the Data Collected during the Peak Shaving Test on 1/12/16.

The load profile of the building is now be altered during peak times, showing that energy storage can be used for peak shaving with enough capacity to get through the peak time.

6.5 ESS ENERGY STORAGE CAPACITY

The data required for this performance objective was power output of the ESS and recorded time of the power output. This was captured on two different days of performing this test, November 15, 2015, and November 17, 2015.

The measurement of power over time was analyzed and the energy capacity of the system was calculated to be the integral of the graph from the beginning of discharge to the time that the power output of the battery reaches zero. The data collected on both days was integrated over the time that the battery was discharging to determine the total discharge energy from the ESS. The summary of the data is shown in Figure 27 and Figure 28 below. The ESS achieved 281 kWh of energy capacity when discharged at 232 kW power output and 294 kWh when discharged at 190 kW power output.

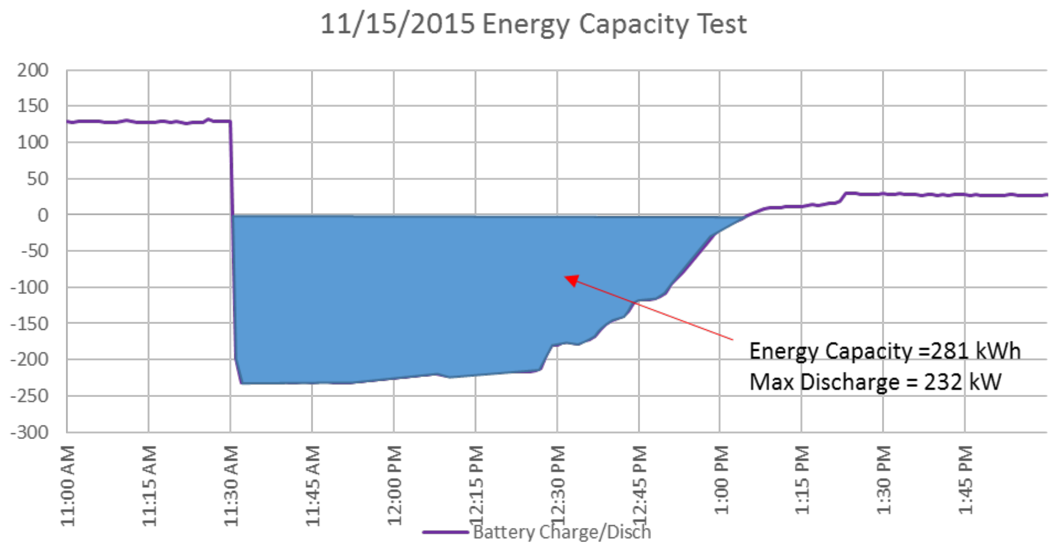

Figure 27. Energy Capacity Calculated for 11/15/15 Test.

Energy capacity at 232 kW power output was 281 kWh.

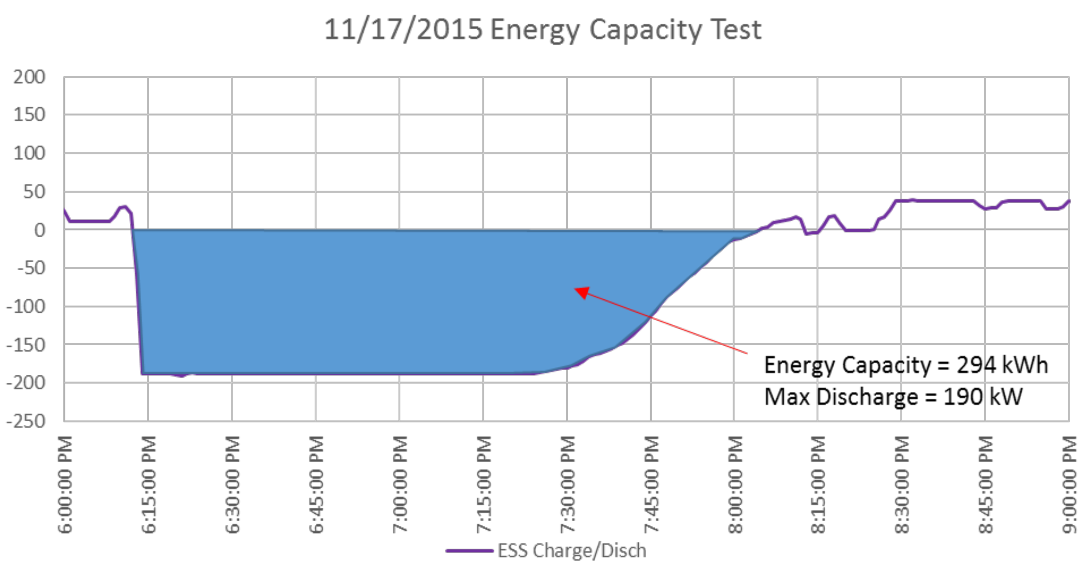

Figure 28. Energy Capacity Calculated for 11/17/15 Test.

Energy capacity at 190 kW power output was 294 kWh.

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7.0 COST ASSESSMENT

7.1 COST MODEL

Putting a cost assessment to the energy security aspect of this project is very difficult. NREL has designed a method using a Customer Damage Function (CDF) that aims to determine interruption costs as a function of outage duration (Giraldez 2012). The CDF function for MCAS Miramar was calculated to be $725/kW peak in a non-emergency situation for the islanding duration objective of 72 hours. Since the system was only able to achieve a maximum theoretical islanding duration of seven hours, that was the number used to calculate the CDF. This puts the CDF at $120/kW peak for a non-emergency situation (Figure 29).

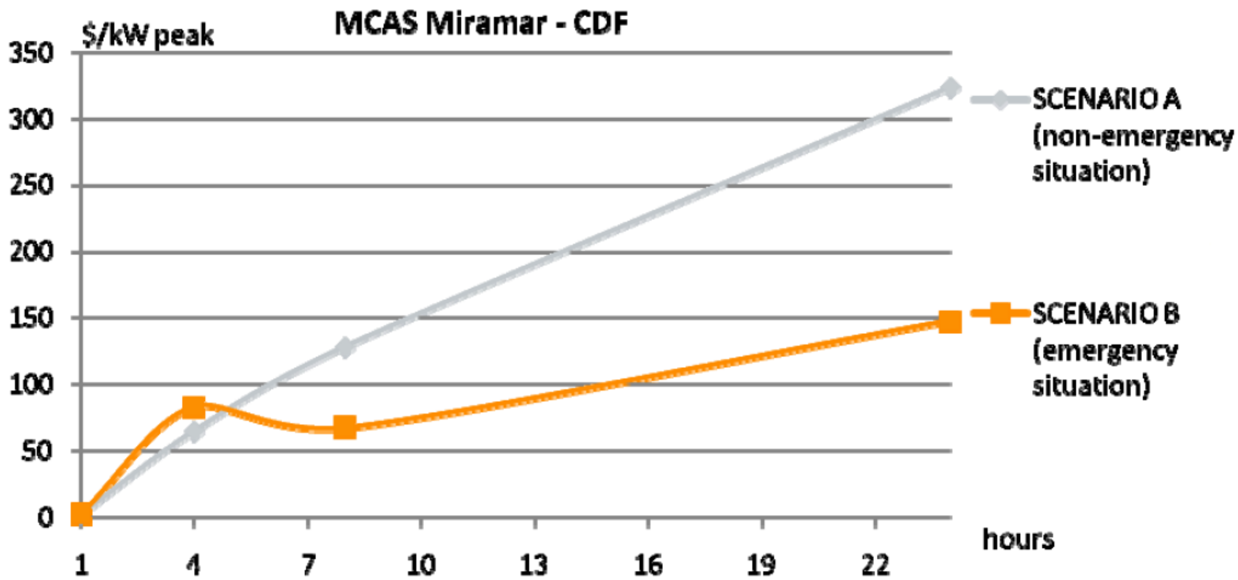

Figure 29: Graphic of CDF from NREL Study in 2012 (Giraldez 2012).

Since Building 6311 had a maximum peak of 130 kW in 2012, the cost associated with an outage of seven hours at Building 6311 would be $15,600. According to SDG&E records over the last 10 years, there were two spikes of outages recorded that impacted customers in 2003 and 2011; therefore, it was assumed that over a 20-year period of operation, the Zn/Br ESS installation will be used twice for back-up operations, and assumed to happen at Year 1 and Year 10.

Since the probability of an outage occurring is rare, economic benefit to the end user will be realized through the system's peak shaving mode. This benefit was also used to calculate the operational cost reductions when using the system in addition to abating the CDF associated with an outage.

The annual savings for operating in peak shaving mode were calculated using load data from MCAS Miramar and SDG&E's 2014 AL-TOU rate sheet for energy calculations. Figure 30 and Figure 31 show the AL-TOU rate schedule. The model used controls the energy storage unit to charge during off-peak times and discharge during peak times. SDG&E has different peak times for winter and summer operations, so the energy storage unit was controlled differently during the winter and summer.

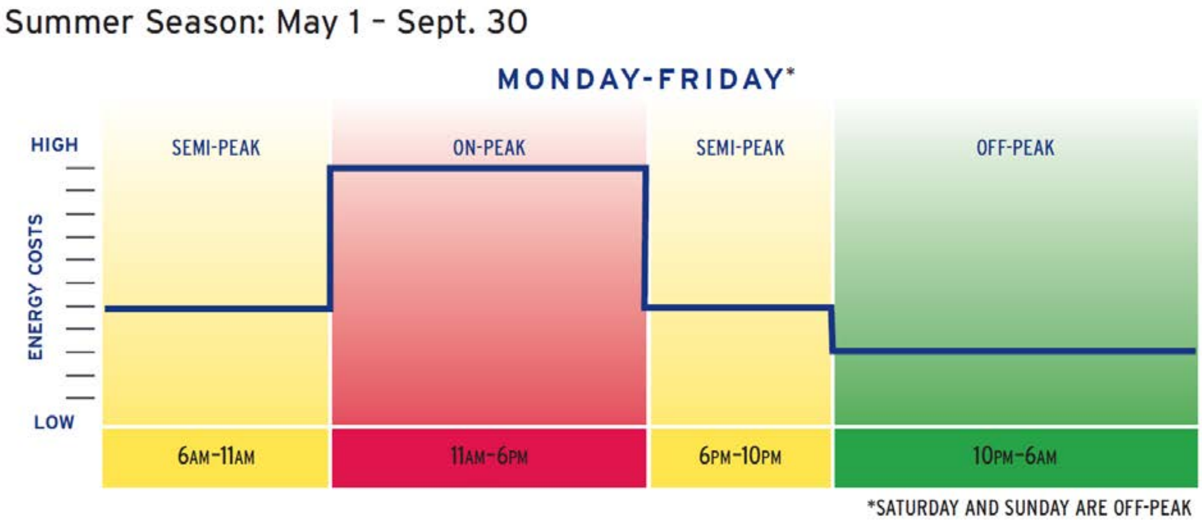

Figure 30. SDG&E Summer Season AL-TOU Schedule.

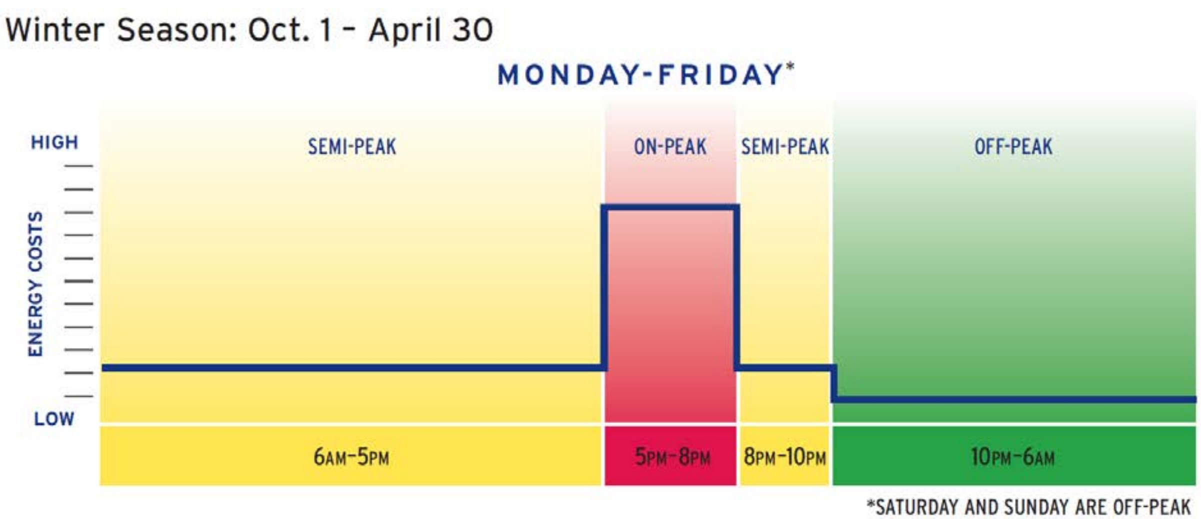

Figure 31. SDG&E Winter Season AL-TOU Schedule.

The model was run for a year's profile. For each billing month the non-coincidental peak, the on-peak peak, and the energy charges were calculated for the normal load curve and the grid purchases curve when using the ESS in peak shaving mode. The result of the model showed there was a $37,000 saving in demand charges and energy charges when using the ESS in peak shaving mode.

The cost elements associated with this assessment are shown in Table 6 below.

Table 6. Cost Model for Energy or Water Technology.

Cost Element	Data Tracked During the Demonstration
Hardware capital costs	ESS $840k, IPEM $41k
Installation costs	Primus Power $37k, Dynalectric Construction $519k
Consumables	No consumables used.
Facility operational costs	$10k/year operational cost savings when used in peak shaving mode
Maintenance	ESS requires annual maintenance at $30k /year
Hardware lifetime	ESS cells are designed to last 20 years
Operator training	$30k for operator training
Salvage Value	Removal of equipment is $67k and the salvage value is $471k using single present value (SPV) calculation from National Institute of Standards and Technology (NIST) Handbook 135.
CDF Abatement	$15.6k twice over 20 years

Total Lifecycle Costs (TLC) for the system assumes a 20-year life and includes the following:

TLC = [Hardware capital costs] + [Installation costs] + [Operator training] + [UPV Maintenance Costs] - [UPV* Operational Cost Reductions] - [SPV Salvage Value] – [CDF Abatement]

UPV Maintenance Costs

UPV Maintenance Costs are calculated using NIST Handbook 135.

$$UPV\ Maintenance\ Costs = AxUPV_N$$

Where A = $30k

UPV_N = 14.88 taken from Table A-2 in NIST Handbook 135 Annual Supplement

UPV Maintenance Costs = $446k

UPV* Operational Cost Reductions

UPV* Operational Cost Reductions are calculated using NIST Handbook 135

$$UPV^*\ Operational\ Cost\ Reductions = AxUPV_N^*$$

Where A = $10k based on using SDG&E AL-TOU Primary rate sheet and peak shaving performance demonstrated for 40kW of peak shaving in the summer and 100kW of peak shaving in the winter.

UPV^*_N = 20 taken from Table A-3a in NIST Handbook 135 Annual Supplement using a 3% increase in price.

UPV* Operational Cost Reductions = $200k

SPV Salvage Value

SPV Salvage Value is calculated using NIST Handbook 135.

$$SPV\ Salvage\ Value = CxSPV_t$$

Where C = $840k

SPV_t = 0.554 taken from Table A-1 in NIST Handbook 135 Annual Supplement

SPV Salvage Value = $465k

<u>CDF Abatement</u>

CDF abatement consists of two values, an abatement assumed at year 1 and an abatement assumed at year 10. The abatement at year one is $15.6k based on the CDF function described earlier. The abatement at year 10 is calculated using SPV in NIST Handbook 135 Annual Supplement.

$$CDF\ Abatement = A + A\ x\ SPV_t$$

Where A = $15.6k based on using SDG&E AL-TOU Primary rate sheet

SPV_t = 0.744 taken from Table A-1 in NIST Handbook 135 Annual Supplement

CDF Abatement = $27.2k

Using the formulas above and date from Table 6. Cost model for energy or water yields the following results for TLC.

TLC = [$881k] + [$556k] + [$30k] + [$446k] - [$200k] - [$465k] – [27.2k] = ~1,221k

The TLC for this system is $1,221k over a 20-year period and is shown in Table 7 for each year. The cost model indicates that with the current performance of the system, the cost savings due to operating the system do not generate a full payback within 20 years. The cost model if the system achieved the original performance objectives is described in Section 7.3.

Table 7. TLC by Year for a 20-year Period.

Year	UPV* Operational Cost Reductions	SPV Salvage Value	UPV Maintenance Costs	CDF Abatement	TLC
1	($10,065)	($815,640)	$29,100	($15,600)	$654,795
2	($20,130)	($792,120)	$57,300		$696,450
3	($30,195)	($768,600)	$84,900		$737,505
4	($40,260)	($745,920)	$111,600		$776,820
5	($50,325)	($724,920)	$137,400		$813,555
6	($60,390)	($703,080)	$162,600		$850,530
7	($70,455)	($682,920)	$186,900		$884,925
8	($80,520)	($662,760)	$210,600		$918,720
9	($90,585)	($643,440)	$233,700		$951,075
10	($100,650)	($624,960)	$255,900	($11,606)	$970,084
11	($110,715)	($606,480)	$277,500		$1,000,099
12	($120,780)	($588,840)	$298,500		$1,028,674
13	($130,845)	($572,040)	$318,900		$1,055,809
14	($140,910)	($555,240)	$339,000		$1,082,644
15	($150,975)	($539,280)	$358,200		$1,107,739
16	($161,040)	($523,320)	$376,800		$1,132,234
17	($171,105)	($508,200)	$395,100		$1,155,589
18	($181,170)	($493,080)	$412,500		$1,178,044
19	($191,235)	($478,800)	$429,600		$1,199,359
20	($201,300)	($465,360)	$446,400		$1,219,534

7.2 COST DRIVERS

For this particular project, since the energy storage technology was scaling up its system for the first time, there were cost drivers associated with building the first large prototype. Developing a scalable, low-cost manufacturing process takes time and investment. Primus was able to balance the uncertain costs of building a first-of-its-kind unit with the unknown costs that are normally associated with developmental technologies. Because of anticipated delays in manufacturing and increased costs associated with developing their manufacturing line, Primus had to deliver a system that was fully functional and tested, albeit at reduced performance levels due to the high costs of their Generation 1 prototype. Going through the experience of building their first full-scale system has allowed Primus to understand the behavior and performance of their system at scale. This has been applied to a Generation 2 version that is capable of meeting the performance objectives of the original system at the anticipated original costs.

Other cost drivers for this type of technology implementations are the siting and infrastructure upgrades required to accommodate new generation assets on an older distribution system. One of the large costs associated with the installation of this project was the upgrades to the switchgear and the transformer, as well as the creation of a concrete pad for the ESS to sit upon properly.

7.3 COST ANALYSIS AND COMPARISON

This section describes the cost analysis for a fully functional system that is capable of meeting the performance goals (such as Generation 2 of Primus' system).

The cost elements associated with this assessment are shown in Table 8 below.

Table 8. Cost Model for an Energy or Water Technology.

Cost Element	Data Tracked During the Demonstration
Hardware capital costs	ESS $840k, IPEM $41k
Installation costs	Primus Power $37k, Dynalectric Construction $519k
Consumables	No consumables used
Facility operational costs	$37k/year operational cost savings when used in peak shaving mode
Maintenance	ESS requires annual maintenance at $30k/year
Hardware lifetime	ESS EnergyCells are designed to last 20 years
Operator training	$30k for operator training
Salvage Value	Removal of equipment is $67k and the salvage value is $471k using SPV calculation from NIST Handbook 135.
CDF Abatement	$94k twice over 20 years

TLC for the system assumes a 20-year life and includes the following:

TLC = [Hardware capital costs] + [Installation costs] + [Operator training] + [UPV Maintenance Costs] - [UPV* Operational Cost Reductions] - [SPV Salvage Value] – [CDF Abatement]

<u>UPV Maintenance Costs</u>

UPV Maintenance Costs are calculated using NIST Handbook 135.

$$UPV\ Maintenance\ Costs = AxUPV_N$$

Where A = $30k

UPV$_N$ = 14.88 taken from Table A-2 in NIST Handbook 135 Annual Supplement

UPV Maintenance Costs = $446k

<u>UPV* Operational Cost Reductions</u>

UPV* Operational Cost Reductions are calculated using NIST Handbook 135

$$UPV^*\ Operational\ Cost\ Reductions = AxUPV_N^*$$

Where A = $37k based on using SDG&E AL-TOU Primary rate sheet

UPV$^*_N$ = 20 taken from Table A-3a in NIST Handbook 135 Annual Supplement using a 3% increase in price.

UPV* Operational Cost Reductions = $740k

<u>SPV Salvage Value</u>

SPV Salvage Value is calculated using NIST Handbook 135.

$$SPV\ Salvage\ Value = CxSPV_t$$

Where C = $840k

SPV$_t$ = 0.554 taken from Table A-1 in NIST Handbook 135 Annual Supplement

SPV Salvage Value = $465k

<u>CDF Abatement</u>

CDF abatement consists of two values, an abatement assumed at year 1 and an abatement assumed at year 10. The abatement at year one is $94. The abatement at year 10 is calculated using SPV in NIST Handbook 135 Annual Supplement.

$$CDF\ Abatement = A + A\ x\ SPV_t$$

Where A = $94k based on using SDG&E AL-TOU Primary rate sheet

SPV$_t$ = 10 taken from Table A-1 in NIST Handbook 135 Annual Supplement using a 3% increase in price.

CDF Abatement = $164k

Using the formulas above and date from Table 8. Cost model for an energy or water yields the following results for TLC.

TLC = [$881k] + [$556k] + [$30k] + [$446k] - [$740k] - [$465k] – [164k] = $544k

The TLC for this system is $544k over a 20-year period and is shown in Table 9. TLC for each year for a 20-year period.

Table 9. TLC for each Year for a 20-year Period.

Year	UPV* Operational Cost Reductions	SPV Salvage Value	UPV Maintenance Costs	CDF Abatement	TLC
1	($37,000)	($815,640)	$29,100	($94,000)	$549,460
2	($74,000)	($792,120)	$57,300		$564,180
3	($111,000)	($768,600)	$84,900		$578,300
4	($148,000)	($745,920)	$111,600		$590,680
5	($185,000)	($724,920)	$137,400		$600,480
6	($222,000)	($703,080)	$162,600		$610,520
7	($259,000)	($682,920)	$186,900		$617,980
8	($296,000)	($662,760)	$210,600		$624,840
9	($333,000)	($643,440)	$233,700		$630,260
10	($370,000)	($624,960)	$255,900	($69,936)	$564,004
11	($407,000)	($606,480)	$277,500		$567,084
12	($444,000)	($588,840)	$298,500		$568,724
13	($481,000)	($572,040)	$318,900		$568,924
14	($518,000)	($555,240)	$339,000		$568,824
15	($555,000)	($539,280)	$358,200		$566,984
16	($592,000)	($523,320)	$376,800		$564,544
17	($629,000)	($508,200)	$395,100		$560,964
18	($666,000)	($493,080)	$412,500		$556,484
19	($703,000)	($478,800)	$429,600		$550,864
20	($740,000)	($465,360)	$446,400		$544,104

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8.0 IMPLEMENTATION ISSUES

This program spans from inception in 2011 to the end of 2015. There were multiple challenges in implementing this program, but only a few standout implementation issues will be noted in this section.

New Technology Development

Some of the challenges of achieving the desired islanding duration can be attributed to working with technologies that were still in their final development phases. A lesson learned as part of the experience with working in the energy storage space is that it is very difficult to scale systems up to utility scale. Fielding technologies that have been demonstrated in relevant lab environments is always a challenge and requires iterations and lessons learned to optimize designs. This was realized early in this project when the original energy storage company that was proposed was not able to build the required unit due to challenges that arose in scaled units that were initially fielded. When Primus was selected as the ESS supplier, the team had to manage a company that had promising technology despite their system being lower on the Technology Readiness Level (TRL) scale than the original proposed supplier (Primus was at TRL4 whereas the original proposed supplier was at TRL 6). This required the team to simultaneously manage and scale up a promising technology that was in final development. The team was challenged with making hard decisions to continuously balance project performance, risk, and cost to meet the intent of the demonstration objectives within budget.

Interconnect Agreement

As this program spanned multiple years, the process of obtaining the IA from SDG&E took some mutual understanding and effort. The use of large scale ESSs in microgrid capacities was new to the utility industry for behind-the-meter applications. Thus the IA process was changing real time for utilities to adapt to how these systems will be deployed. This project was subject to some of the real-time changes as a few iterations of the application were required due to changing application requirements. Ultimately the IA and permit to operate were granted due to the hard work of multiple parties; however, it is still unclear if there is a well-defined process for getting IAs in place for microgrids.

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9.0 REFERENCES

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